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A Dissertation
by
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ABSTRACT

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The next pages are Dedication, Acknowledgments, Contributors and Funding Sources, and Nomenclature. Of these, Contributors and Funding Sources is required. The rest are optional.

DEDICATION

To my mother, my father, my grandfather, and my grandmother. To see what happens with multiple lines, I extend this next part into a second line.

ACKNOWLEDGMENTS

This section is also optional, limited to four pages. It must follow the Dedication Page (or Abstract, if no Dedication). If listing preliminary pages in Table of Contents, include Acknowledgments. Heading (ACKNOWLEDGMENTS) is bold if major headings are bold. It should be in same type size and style as text. So does vertical spacing, paragraph style, and margins. Also, ensure that the spelling of “acknowledgments” matches throughout the text and the table of contents.

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Contributors

This work was supported by a thesis (or) dissertation committee consisting of Professor XXXX [advisor – also note if co-advisor] and XXX of the Department of [Home Department] and Professor(s) XXXX of the Department of [Outside Department].

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All other work conducted for the thesis (or) dissertation was completed by the student independently.

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NOMENCLATURE

OGAPS	Office of Graduate and Professional Studies at Texas A&M University
B/CS	Bryan and College Station
TAMU	Texas A&M University
SDCC	San Diego Comic-Con
EVIL	Every Villain is Lemons
EPCC	Educator Preparation and Certification Center at Texas A&M University - San Antonio
FFT	Fast Fourier Transform
ARIMA	Autoregressive Integrated Moving Average
SSD	Solid State Drive
HDD	Hard Disk Drive
O&M	Eller Oceanography and Meteorology Building
DOS	Disk Operating System
HDMI	High Definition Multimedia Interface
L^1	Space of absolutely Lebesgue integrable functions; i.e., $\int f < \infty$
L^2	Space of square-Lebesgue-integrable functions, i.e., $\int f ^2 < \infty$
$PC(S)$	Space of piecewise-continuous functions on S
GNU	GNU is Not Unix
GUI	Graphical User Interface
PID	Principal Integral Domain

MIP	Mixed Integer Program
LP	Linear Program

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1. NANOSCOPY USING A SEMICONDUCTOR HETEROSTRUCTURE AS THE SAMPLE STAGE

1.1 Abstract

A special structured illumination microscopy scheme using a two dimensional electron gas as the sample stage is proposed. Terahertz plasma waves generated by a current-driven instability illuminate the sample. Concurrently, a plane wave is used to shift the plasmonic pattern needed to expand the observable range of spatial frequencies. Full coverage of the spatial frequency regime is obtained by tuning the plasma waves through gate voltage control. Hence, it is possible to reconstruct an image with resolution up to two orders of magnitude beyond the diffraction limit. Due to the linear nature of the technique, only a weak illumination signal is required, therefore minimizing the likelihood of sample damage due to radiation.

1.2 Introduction

In conventional wide-field fluorescent microscopy, a sample is uniformly illuminated by a beam of light, and the resulting fluorescence is observed in the far-field through the objective lens. The uniform intensity of the illumination along the sample fundamentally restricts the resolution of the system to half the wavelength of light due to the Abbe diffraction limit. With ever growing need to image minuscule objects especially in life sciences, modern microscopy techniques such as confocal and linear structured illumination microscopy (SIM) use spatially non-uniform sources of light to illuminate the sample. This non-uniformity is directly attributed to obtaining resolution that can be extended beyond the diffraction limit by a factor of 2 [2, 3]. Use of pinholes in confocal microscopy makes the technique highly inefficient as a significant part of light is discarded that may leave weakly fluorescent objects

undetectable. Structured Illumination microscopy is a wide-field technique in which a fine illumination pattern such as a sinusoidal standing wave is used to generate *Moiré fringes* in the observed image [4, 5]. The high frequency content is mathematically reconstructed from a series of images acquired by shifting the pattern. Using a non-linear version of SIM, theoretically unlimited resolution can be achieved [6]. However, high levels of illumination intensity are required, subjecting the sample to significant radiation damage.

Resolution beyond the classical diffraction by a factor greater than 2 can be realized when an object is illuminated by surface waves, that are electromagnetic waves found at a material interface where one of the media possesses a complex dielectric function with a negative real part. The wavelength and phase velocity of the surface waves are much smaller than the homogeneous waves at the same frequency in a given medium. Using a grating structure to generate the surface waves with sub-diffraction features, a resolution with magnification factor of 20 was first demonstrated at optical frequencies by Nassenstein [7]. Recently, a plasmonic structured illumination microscopy (PSIM) technique was proposed in which a sample was excited by surface plasmons existing at a metal-dielectric interface in the optical frequency range [8]. In another scheme, it was shown that a hundred-fold resolution enhancement is possible using mid-infrared graphene plasmons [9].

Current-drive plasma instabilities have mainly been studied in the context of ionized gases [10]. An analogous activity leads to generation of plasma waves in solid-state devices [11] that has led to many interesting applications in the far-infrared frequency region [12, 13]. A two-dimensional electron gas (2DEG) is formed at the interface of epitaxially grown semiconductors that acts as a transistor channel. In addition to the unusually high electron mobility, free-electron densities that are comparable to metals are observed without any intentional doping in the channel.

Plasma waves originating in the electron channel of field-effect transistors which is only a few atoms thick were discovered more than 40 years ago [14, 15] when excited by an external TM polarized plane wave. Field-effect transistor plasma waves have of late received great interest because of their application in engineering terahertz frequency sources and sensors [16, 17, 18, 19, 20]. Although research has mainly been focused in realizing far-infrared devices, nitride based heterostructures have been used for the mid-infrared frequencies [21]. More importantly, the frequency response of the device can be tuned by varying the gate voltage [22, 23].

In this paper, a nanoscale imaging technique is presented in which subwavelength plasma waves, generated by a current in a transistor channel that can be tuned by controlling gate voltage, are used as the illumination pattern required for SIM. The configuration effectively creates a much larger observable spatial frequency region as compared to a far-infrared (terahertz) plane wave. Due to the linear nature of the scheme, resolution of up to two orders of magnitude beyond the diffraction limit can be obtained with a weak field intensity. Although the wavelength is very small along the channel, it simultaneously brings the disadvantage of a fast decay in the vertical direction. The presence of a semiconductor layer above the channel further reduces the intensity of the wave. The resolution enhancement is ultimately limited by the layer thickness which should be kept as small as the fabrication process permits in order to reduce attenuation of the standing wave in the vertical direction.

1.3 Theory

1.3.1 Dispersion relation

A schematic diagram of the proposed system which is similar to a transistor, is shown in Fig. 1.1 where a 2DEG that acts as a transistor channel is formed at the interface of two semiconductor materials of slightly different band-gap energies.

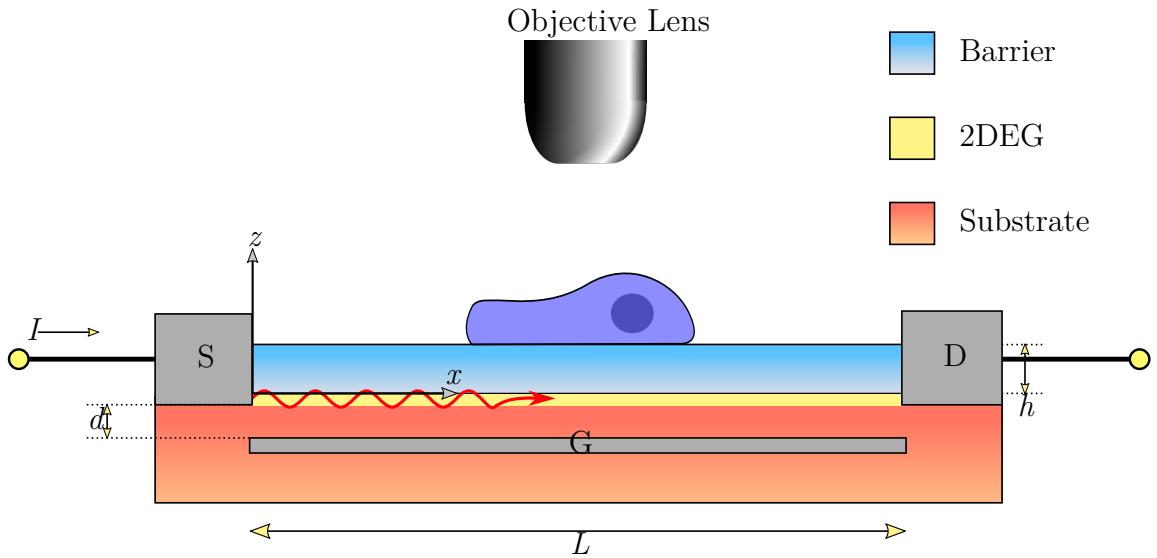


Figure 1.1: Illustration of the imaging scheme where sample is excited by plasma wave pattern generated underneath by a current-driven instability

Plasma waves are generated in the channel when the source and drain terminals are driven by a current source. Due to reflections from the conducting boundaries, the channel region forms a cavity in which the plasma waves form a standing wave. The structure is backed by a gate terminal that spans the length L of the channel and spaced a distance d below the 2DEG. The gate capacitively couples with the 2DEG, and by varying the voltage, the velocity as well as concentration of electrons in the channel can be controlled. A barrier layer of thickness h separates the sample from the 2DEG.

The compressed nature of the plasma waves can be described by its dispersion relation. Here, we consider the sample stage which is terminated by a gate at the bottom and free-space at the top, excited by a TM polarized plane wave. The effects of the drain and source terminals are ignored by assuming the layered semiconductor structure along with the 2DEG channel to be of infinite lateral extent. The dispersion relation which shows a frequency dependent resonance response of plasma waves in

the 2D channel, is obtained by imposing the transverse resonance condition realized by an equivalent transmission line (TL) circuit [24, 25]. The 2DEG is modeled as a shunt admittance related to Drude-type surface conductivity [26],

$$Y_\sigma = \sigma_s = \frac{N_s e^2 \tau}{m^*} \frac{1}{1 + j\omega\tau}, \quad (1.1)$$

where N_s is the surface electron density in the channel, e is the electron charge, m^* is the effective electron mass in the heterostructure, τ is the scattering time of electrons, and ω is the angular frequency. The dispersion relation is then written as [27]:

$$Y^\uparrow(z_0) + Y^\downarrow(z_0) + Y_\sigma = 0. \quad (1.2)$$

Here, $Y^\uparrow(z_0)$ and $Y^\downarrow(z_0)$ are the up- and down-looking TL admittances from the 2DEG located at $z = 0$, and expressed as:

$$Y^\uparrow(z_0) = Y_2 \frac{1 - \Gamma^\uparrow(z_0)}{1 + \Gamma^\uparrow(z_0)}, \quad (1.3a)$$

$$Y^\downarrow(z_0) = -jY_1 \cot(k_{z1}h). \quad (1.3b)$$

For each layer, Y_i and k_{zi} where $i = 0, 1, 2$ are the respective TM mode admittance and transverse wavenumber of free-space, barrier and substrate layers respectively given by:

$$Y_i = \frac{\omega \varepsilon_i \varepsilon_0}{k_{zi}}, \quad k_{zi} = \pm \sqrt{k_0^2 \varepsilon_i - k_x^2} \quad (1.4)$$

where ε_i is the relative permittivity of i^{th} layer and k_x is the longitudinal propagation constant of the structure. The upward-looking reflection coefficient Γ^\uparrow in (1.3a) is

expressed in terms of the TM mode admittances:

$$\Gamma^\uparrow(z_0) = \frac{Y_1 - Y_0}{Y_0 + Y_1} e^{-2jk_{z2}d_1} \quad (1.5)$$

A closed-form expression for the longitudinal propagation constant k_x by solving (2.4) is tedious, therefore numerical root-finding techniques such as the Newton method [28] have to be employed. As an example, the dispersion diagram of a AlGaN/GaN heterostructure is shown in Fig. 2.6 with no gate bias applied along with a light line whose slope is multiplied by a factor of 90 for illustration. The real part corresponds to propagation and imaginary part accounts for decay of the wave. The result is similar to a gated 2DEG plasmons in which the gate terminal is located at the top [29, 30]. At 25 THz, the plasma wavenumber is approximately 80 times greater than that of free-space with negligible loss. Such extreme subwavelength phenomenon makes super-resolution possible. The structure parameters used to compute the dispersion relation via (1.1)-(1.5) are now briefly discussed.

The gate-channel separation is $d = 100$ nm. The channel length L is 2 μm whereas the AlGaN barrier layer is $h = 20$ nm wide. The permittivity of both semiconductor layers is approximated to the static value, i.e., $\varepsilon_1 \approx \varepsilon_2 = 9.5$ when the mole-fraction of aluminum in AlGaN alloy is taken as 0.2 [31]. A surface carrier density of $N_s = 5 \times 10^{13} \text{ cm}^{-2}$ and scattering time τ of 114 ps corresponding to a temperature of 3 K is assumed. As the temperature is increased, τ gets smaller which leads to reduced mobility and introduces loss in the channel. Through the gate voltage V_g , the electron density N_s of the channel can be varied using:

$$N_s = N_0 \times \left(1 - \frac{V_g}{V_T}\right), \quad (1.6)$$

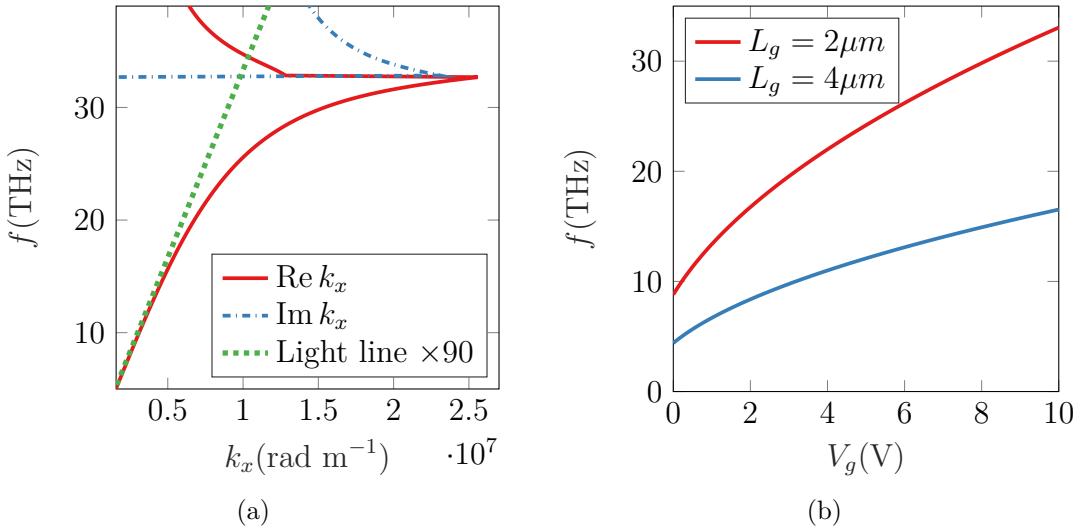


Figure 1.2: (a) Plasma wave Dispersion diagram for the transistor structure supporting a 2DEG channel. (b) Effect of gate voltage on resonant frequency

where N_0 is the zero-bias density and V_T is the gate threshold voltage of the transistor. For a channel terminated by highly conducting source and drain terminals at each side, the resonant frequency as a function of carrier density is expressed as [32]:

$$\omega = \sqrt{\frac{N_s e^2 d}{m_* \varepsilon} \frac{\pi}{L}} \quad (1.7)$$

where ε is the average permittivity of the surrounding media. Using (1.6) and (1.7), the tunability of plasma waves assuming a gate threshold voltage of -0.764 V is shown in Fig. 1.2b. As expected, increasing the length of the channel reduces the resonant frequency.

1.3.2 Image Reconstruction

At low loss, the plasma wave illumination pattern $I(\mathbf{r})$ can be assumed sinusoidal and expressed as:

$$I(\mathbf{r}) = 1 + \cos(\mathbf{k}_\rho \cdot \mathbf{r} + \phi) \quad (1.8)$$

where $\mathbf{k}_\rho = k_x \hat{\mathbf{x}} + k_y \hat{\mathbf{y}}$ is the spatial frequency wavevector, $\mathbf{r} = x \hat{\mathbf{x}} + y \hat{\mathbf{y}}$ is the two-dimensional positional vector and ϕ is the pattern phase. An image $M(\mathbf{r})$ of a sample atom distribution $F(\mathbf{r})$ observed through a microscope can be expressed as:

$$M(\mathbf{r}) = [F(\mathbf{r}) \cdot I(\mathbf{r})] \otimes H(\mathbf{r}) \quad (1.9)$$

where $H(\mathbf{r})$ is the point spread function (PSF) of the microscope, and \cdot, \otimes denote multiplication and convolution operations in the spatial domain respectively. A frequency domain representation of the image obtained by taking the Fourier transform of (1.9) is expressed as:

$$\begin{aligned} \tilde{M}(\mathbf{k}) &= [\tilde{F}(\mathbf{k}) \otimes \tilde{I}(\mathbf{k})] \cdot \tilde{H}(\mathbf{k}) \\ &= \frac{1}{2} [2\tilde{F}(\mathbf{k}) + \tilde{F}(\mathbf{k} - \mathbf{k}_\rho)e^{-j\phi} + \tilde{F}(\mathbf{k} + \mathbf{k}_\rho)e^{j\phi}] \cdot \tilde{H}(\mathbf{k}) \end{aligned} \quad (1.10)$$

where \sim over the letters indicates a frequency domain term and $\tilde{H}(k)$ is the optical transfer function (OTF) of the microscope. A spatial frequency representation of the scheme is illustrated in Fig. 1.3. Assuming a numerical aperture of (NA) of unity, the OTF can be described by a circular disc as shown in Fig. 1.3(a) where the passband is bounded by $\sqrt{k_x^2 + k_y^2} = \nu$. As evident in (1.10), a sinusoidal illumination pattern has three frequency components which generates an image that is a linear combination of the sample along with two shifted versions as shown in Fig. 1.3(b). To reconstruct the sample, three different images need to be captured with each

possessing a different phase term ϕ . The process can be expressed as a system of linear equations,

$$\tilde{H}(\mathbf{k}) \cdot \begin{bmatrix} \tilde{F}(\mathbf{k}) \\ \tilde{F}(\mathbf{k} - \mathbf{k}_\rho) \\ \tilde{F}(\mathbf{k} + \mathbf{k}_\rho) \end{bmatrix} = \begin{bmatrix} 2 & e^{-j\phi_1} & e^{j\phi_1} \\ 2 & e^{-j\phi_2} & e^{j\phi_2} \\ 2 & e^{-j\phi_3} & e^{j\phi_3} \end{bmatrix}^{-1} \begin{bmatrix} \tilde{M}_1(\mathbf{k}) \\ \tilde{M}_2(\mathbf{k}) \\ \tilde{M}_3(\mathbf{k}) \end{bmatrix} \quad (1.11)$$

The phase shifts in (1.11) are known beforehand. Frequency content of the sample up to k_ρ can, therefore be observed due the Moiré effect which transports the high frequency information in to the observation region. To achieve two-dimensional enhancement in resolution, either the sample must be rotated about the optical axis of the microscope or the angular distribution of the illumination needs to be varied. The performance in terms of imaging speed can be improved by exciting the sample further with a pulse having energy higher than the plasmon illumination [33]. In the spatial frequency space, this corresponds to an enlarged OTF depicted by light-colored discs with radius v in Fig. 1.3. Fewer tuned plasmon frequencies are therefore, required to achieve full coverage of the enlarged frequency region. In this scheme, an external plane wave is used to shift the plasma wave pattern laterally in the sample stage. The electric field of a TM polarized plane wave is expressed as, $\mathbf{E}_{ext} = \hat{\mathbf{x}}a + \hat{\mathbf{z}}b$. The total field at the surface is the sum of the plasmonic field and external plane wave. The total intensity is then expressed as: where k_ρ is the spatial frequency of plasma wave, $\chi = \sqrt{a^2 + b^2}$ and $\psi = \text{atan}(b/a)$. The field components a and b are controlled by changing the incident angle of the plane wave. Using a commercial full-wave electromagnetic simulation tool [34], lateral shifting of the pattern is shown in Fig. 1.4a. Since the wavelength is much smaller than the channel length, only a small portion is shown. As discussed earlier, the standing

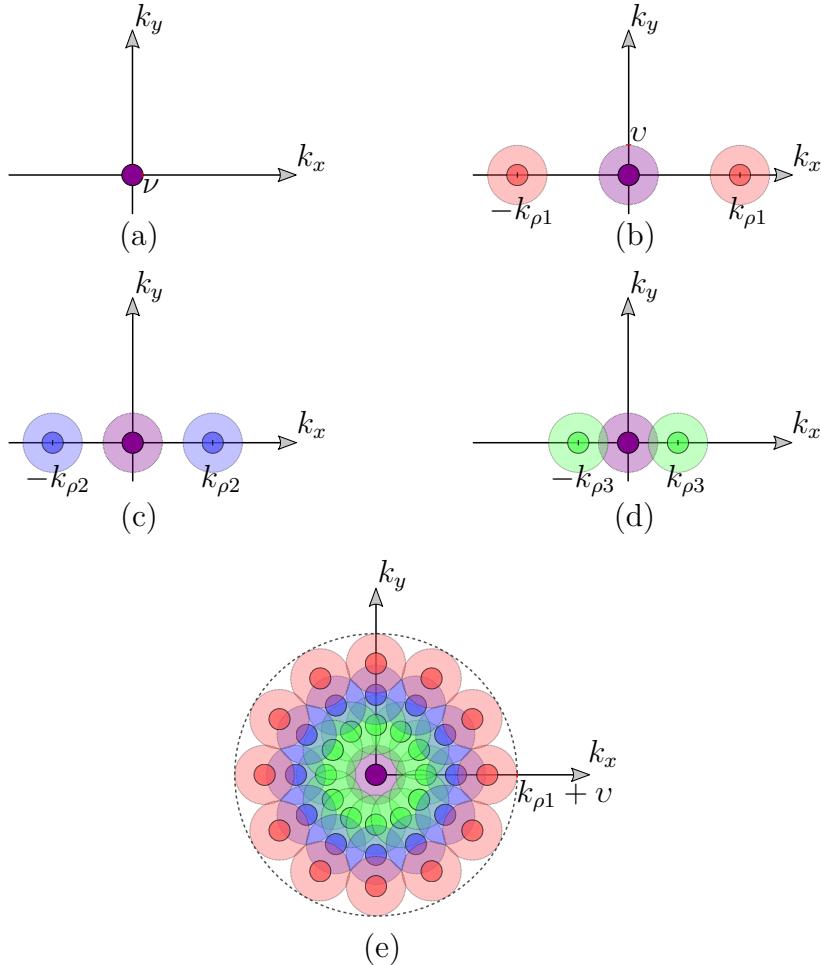


Figure 1.3: Resolution enhancement through SIM: (a) Diffraction limited observable region in frequency domain. Moiré effect using a sinusoidal illumination pattern bringing high frequency content under the observable region. Sample illuminated at different plasma frequencies: (b)-(d). (e) Effective resolution enhancement of $k_{\rho_1} + v$ in two dimensions can be obtained after rotating the sample with respect to the optical axis

wave pattern can be tuned to different frequencies through gate voltage control. Normalized standing wave patterns tuned to different frequencies are shown in Fig. 1.4b that were simulated using commercial full-wave electromagnetic software [34].

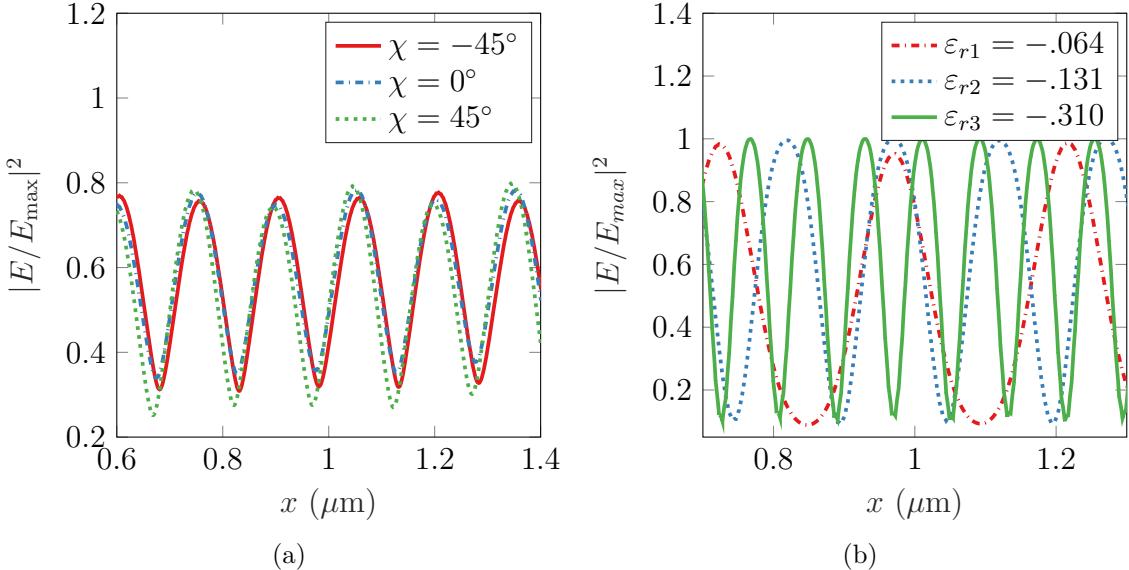


Figure 1.4: Full-wave simulation results: (a) Phase shift achieved by exciting the structure with an external plane wave at an angle. (b) Tuning of the standing wave structure by applying gate bias

1.4 Simulated Results

We consider a sample with atom distribution shown in Fig. 1.5a. Each particle shown has a diameter of 1 nm. The minimum separation between the atoms is 38.2 nm and maximum is 137.3 nm. The 2D plasma waves are generated by a dc current-driven instability at 25 THz, $h\omega = .1$ eV at zero gate bias. It is assumed that NA is 1. To demonstrate the super-resolution technique, the atom distribution is first Fourier transformed to the spatial frequency domain. The critical step to achieve super-resolution reconstruction involves the inverse Fourier transform computed using frequency contents up to a circular region of radius $2k_\rho + v$ where k_ρ can be varied by gate voltage. In Figs. 1.5b and 2.9a, a resolution enhancement 39.5 and 80 is shown that corresponds to 79 nm and 39.5 nm resolution respectively. Figure 1.5b shows that the particles that are separated by a distance less than the

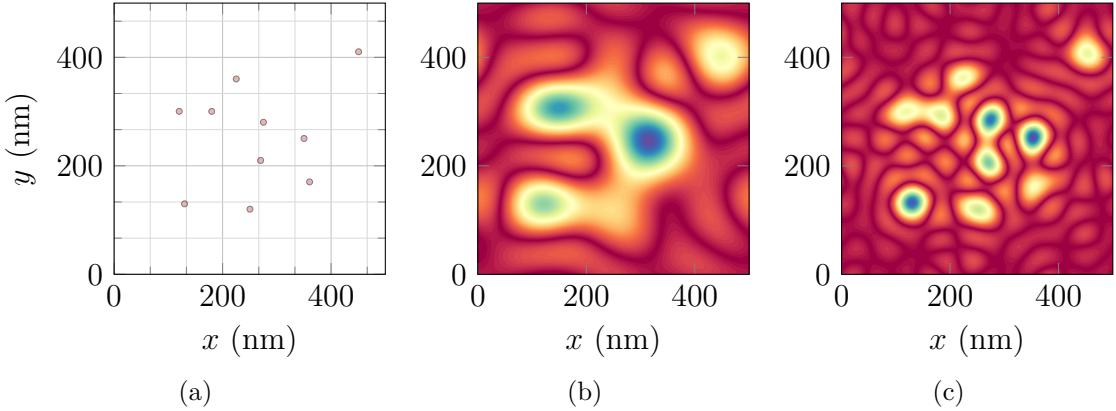


Figure 1.5: (a) Sample distribution. Simulation of the reconstructed sample image at: (b) $\text{Re } k_\rho = 39.5$ (c) $\text{Re } k_\rho = 80$

resolution can not be resolved and appear as a contiguous blurry streak, whereas they are distinguishable in Fig. 2.9a. At cryogenic temperatures, the plasmons exhibit near loss-less behavior in the 2DEG where the real part of the wavenumber is at least three orders of magnitude greater than the imaginary part. However, as the temperature rises, the reduced electron mobility resulting due to electron scattering introduces a plasma wave decay factor such . To account for the loss, the plasma

1.5 Conclusion

We propose a super-resolution nanoscopy scheme based on the subwavelength surface electromagnetic fields found in a semiconductor heterostructure. This method is useful in particular for light-sensitive samples as it requires a weak field intensity for illumination. The temperature dependent electron scattering introduces loss, which degrades the performance of the system with increase in temperature. The image reconstruction algorithm is as efficient as in conventional linear SIM, yet the high wave number along with tunability of the plasma waves allows it to achieve subdiffraction resolution of up to 80 times in the mid-infrared range.

2. OPTICAL NANOANTENNAS*

2.1 Abstract

An overview of the field of optical plasmonic antennas is presented in this chapter. After a brief introduction and historical review, the theory of surface plasmon polaritons which leads to a set of overall observations as to the requirements and restrictions placed on the operation of plasmonic waveguides and antennas is presented. Both a single metal-dielectric interface and two interfaces between a metal sheet with dielectrics on either side are considered. In the second section, the physical principles of operation and mathematical design criteria are presented for several common optical antennas including on-surface metallic structures and free-standing particles. The third section covers the basic theory of aperture radiators along with a more detailed description of some popular designs. Current applications of optical nanoantennas are presented along with a discussion on future directions in the optical nanoantenna research.

2.2 Introduction

Optical nanoantennas (or simply antennas) are nano-sized objects that transmit or receive electromagnetic fields through their intrinsic plasmonic behavior in the optical or near infrared frequency range. Optical antennas have become the object of great interest to engineers due to rapid advancements in nano-device fabrication technologies. In particular, commercial computer aided design (CAD) programs that

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allow the characterization of materials with a negative real part permittivity and the lower cost and advancements in electron beam (e-beam) etching machines, permitting the creation of nano-circuits with line widths on the order of 10 nm or smaller, have made it possible for universities and research labs to not only numerically simulate, but also build models and measure the properties of optical antennas. The fact that practical research and development is now available to the academic and industrial community has led to several new applications and technologies including dramatically improved spectroscopy [35, 36, 37], disease and toxin sensors [38, 39], wireless communication with nano-circuitry [40], and the creation of nano-circuits using subwavelength lithography [41, 42]. The opportunities for antenna engineers in this vast new landscape are great, but much work remains to be carried out on analytical and numerical characterization as well as in developing an understanding as to how electromagnetic and quantum processes can be incorporated into a coherent mathematical theory that will allow rapid and systematic design of such devices.

Dimensions of optical antennas are in the nanometer (nm) range of visible and near infrared light. Typical antenna element shapes include the dipole, bowtie, and aperture as shown in Fig. 2.1. Optical antennas are always fabricated out of noble metals, most commonly gold and silver and less commonly with aluminum, chromium, and copper. Unfortunately, there are some negative aspects of these materials that make them difficult to work with in engineering applications. In an ambient environment silver can form a silver sulfide layer that inhibits the propagation of plasmon waves [43] and as such, is not always a good candidate for an optical antenna. Aluminum has a higher dielectric function imaginary part than does gold, increasing from a small difference at 550 nm to a significantly larger value at 830 nm, where it becomes exceptionally lossy. During the fabrication of a nanoantenna, ion-beam bombardment can cause gold to melt making it hard to form a smooth metallic

structure that is true to its intended design [44]. Nevertheless, noble metals are necessary for the applications described in this chapter because their plasma frequency, a crucial element of the design, lies in the range of visible light. A majority of

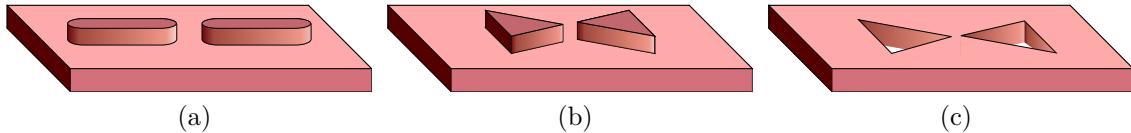


Figure 2.1: Common nanoantenna elements (a) dipole (b) bowtie and (c) aperture. The dipole, bowtie, and aperture antennas are typically etched on a low-loss substrate such as silicon dioxide.

current research papers focus on free-space designs, but for most practical applications, nanoantennas will be etched on a substrate. The type of substrate depends on the particular application, to some extent determined by the mechanism used to excite the antenna, but for many industrial applications, cost and availability considerations have driven the move to silicon dioxide SiO_2 , often described in technical papers simply as ‘glass’. Typical signal generation is via off-board laser light or by an on-board transmission line. Unlike classical antenna signals which can be generated at virtually any microwave carrier frequency, there are a select few frequencies where low-cost optical sources are available, although specialized lasers can operate at frequencies throughout the optical spectrum. In optical terminology the signal has traditionally been specified in wavelengths rather than frequency, however here both terms will be used. Some common wavelengths where research is being carried out are in the neighborhood of 550, 630, and 820 nm. An extensive list of various laser types along with their operating frequencies can be found [45].

A counter-intuitive oddity of noble metals at optical frequencies is that they

are no longer perfect conductors, but rather they have some of the properties of a dielectric with, as mentioned above, a permittivity whose real part is negative. This turns out to be a remarkable advantage over dielectrics with a positive real part, due to the fact that the wavelength of the current in these metals can be much less than the wavelength of the free-space incident field. A solid nanorod still resonates around one-half wavelength of its surface current but, given an incident field frequency, one must use numerical or approximate analytical methods to determine the shorter than free-space wavelength of the antenna at resonance. While optical antennas make excellent resonators, due in part to a tightly bound plasmon current, the wavelength mismatch between air and metal, which does not exist at microwave frequencies, is a significant factor hampering their radiation and receiving properties. To understand how the radiation efficiency of an optical antenna can be improved, it is necessary to first study the unusual properties of waves on metals at optical frequencies. The essentials of optical wave propagation and radiation are presented in the following section.

2.3 Electromagnetic Theory of Surface Plasmon Polaritons

The physical mechanism for wave propagation at optical frequencies is very different from that of propagating waves at microwave frequencies although the mathematics for determining the wave behavior is virtually the same and can be laid out in a classical Sommerfeld integral analysis. At optical frequencies surface plasmon polaritons (SPPs), electromagnetic surface waves created by coherent charge oscillations in an electron gas in a metal, propagate at a metal-dielectric interface [46, 47, 48]. Resonant plasmonic oscillations can also occur in the confined space of nanoparticles [36]. Fortunately, in most cases where optical antennas are concerned, the quantum mechanisms which create SPPs or local confined plasmons can

be expressed in terms of the material properties of metals and nanoparticles, such as shape, size and permittivity [49]. Because the study of nanoantennas relies on the behavior of plasmonic waves, it resides in the research area described as ‘plasmonics’, a subfield of nanophotonics [50, 51]. In this section, some of the basic theory of SPPs will be presented to aid the reader in understanding the underlying principles that determine the behavior of nanoantennas. First, the fundamental problem of electromagnetic propagation on a planar dielectric-metal interface at optical frequencies is considered, followed by a discussion on the role played by quantum effects in determining the allowable frequency range and loss mechanisms in nano-device design. This presentation does not require an understanding of quantum mechanics, but occasionally the quantum electronics terminologies are used to describe the effects that determine the properties of the constitutive parameters at optical frequencies.

2.3.1 Single Boundary Structure

Assuming a metal can have a complex permittivity at optical wavelengths, the propagation constants k_{xi} and k_{zi} at the planar interface between dielectric and metal half-spaces, $i = 1, 2$ respectively, can be found starting with expressions for transverse magnetic (TM) plane waves in these two regions as shown in Fig. 2.2. The electromagnetic field expressions in region 1 where $z \geq 0$ are,

$$\mathbf{E}_1 = (\hat{\mathbf{x}}E_{x1} + \hat{\mathbf{z}}E_{z1}) e^{-j(k_x x + k_{z1} z)}, \quad (2.1a)$$

$$\mathbf{H}_1 = \hat{\mathbf{y}}H_{y1} e^{-j(k_x x + k_{z1} z)} \quad (2.1b)$$

and in region 2 where $z \leq 0$,

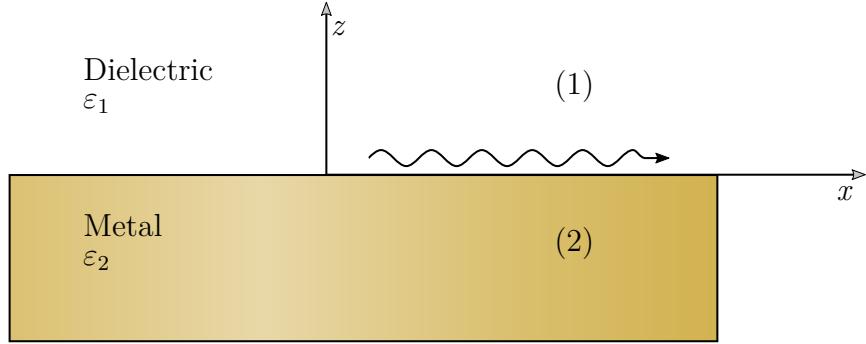


Figure 2.2: Dielectric and metal half-spaces with a planar boundary.

$$\mathbf{E}_2 = (\hat{\mathbf{x}} E_{x2} + \hat{\mathbf{z}} E_{z2}) e^{-j(k_x x - k_{z2} z)}, \quad (2.2a)$$

$$\mathbf{H}_2 = \hat{\mathbf{y}} H_{y2} e^{-j(k_x x - k_{z1} z)}. \quad (2.2b)$$

A positive sign is chosen for k_{z2} to ensure propagation in the negative z direction.

The $\text{Im}(k_z)$ must therefore be negative in order to be bounded at infinity.

Ampere's law, $\nabla \times \mathbf{H} = -j\omega\varepsilon \mathbf{E}$, applied to (2.1) and (2.2) yields the boundary conditions:

$$k_{z1} H_{y1} = \omega \varepsilon_1 E_{x1} \quad (2.3a)$$

$$k_{z2} H_{y2} = -\omega \varepsilon_2 E_{x2} \quad (2.3b)$$

where $\varepsilon_{1,2}$ are the permittivities of the dielectric and metal regions respectively. Since metal at optical frequencies has the behavior of a lossy dielectric, continuity of tangential electric and magnetic fields, $E_{x1} = E_{x2}$ and $H_{y1} = H_{y2}$, can be applied at the boundary along with (2.3). This gives the dispersion relation for waves on the metal-air boundary:

$$\frac{k_{z1}}{\varepsilon_1} + \frac{k_{z2}}{\varepsilon_2} = 0. \quad (2.4)$$

Helmholtz equation, $\nabla^2 \mathbf{E} + k_i^2 \mathbf{E} = 0$, where $i = 1, 2$, and assuming the permeabilities of all regions are that of air, lead to the dispersion equations for the two regions,

$$k_x^2 + k_{zi}^2 = \varepsilon_i \left(\frac{\omega}{c} \right)^2 = \varepsilon_i k_0^2 \quad (2.5)$$

where c is the speed of light in air. Equations (2.4) and (2.5) are combined to produce the SPP propagation constant:

$$k_x = k_0 \sqrt{\frac{\varepsilon_{r1} \varepsilon_{r2}}{\varepsilon_{r1} + \varepsilon_{r2}}} \quad (2.6)$$

where k_0 is the free-space wavenumber and the subscript r is used to indicate a dielectric constant quantity. If the permittivity of the dielectric is real and that of the metal is complex, $\varepsilon_2 = \varepsilon'_2 - j\varepsilon''_2$, and $|\varepsilon'_2| \gg \varepsilon''_2$ the complex propagation constant in (2.6) can be expressed as [48]:

$$k_x = k_0 \left(\frac{\varepsilon_1 \varepsilon'_2}{\varepsilon_1 + \varepsilon'_2} \right)^{1/2} - j k_0 \frac{\varepsilon''_2}{2 \varepsilon'^2_2} \left(\frac{\varepsilon_1 \varepsilon'_2}{\varepsilon_1 + \varepsilon'_2} \right)^{3/2} = k'_x - j k''_x. \quad (2.7)$$

Similarly, from (2.5) and (2.6), k_{zi} becomes approximately,

$$k_{z1} = k_0 \left(\frac{\varepsilon_1^2}{\varepsilon_1 + \varepsilon'_2} \right)^{1/2} + j k_0 \frac{\varepsilon_1 \varepsilon''_2}{2 (\varepsilon_1 + \varepsilon'_2)^{3/2}} = k'_z + j k''_z, \quad (2.8a)$$

$$k_{z2} = k_0 \left(\frac{\varepsilon'^2_2}{\varepsilon_1 + \varepsilon'_2} \right)^{1/2} - j k_0 \frac{\varepsilon''_2 (2\varepsilon_1 + \varepsilon'_2)}{2 (\varepsilon_1 + \varepsilon'_2)^{3/2}} = k'_z - j k''_z. \quad (2.8b)$$

From (2.4)-(2.8), some very important conclusions can be drawn regarding the nature of the two half-space materials and the properties of nano surface waves on their intersecting boundary:

1. First, if loss is neglected ($\varepsilon''_2 \simeq 0$), a valid assumption for noble metals over

significant segments of the optical range so that the permittivities of both regions are real, the equality in (2.4) will not hold if these permittivities are both positive or both negative. But, if the permittivity in the dielectric region 1 is positive, $\varepsilon_1 > 0$, and the real part of the permittivity in the metal region 2 is negative, $\varepsilon'_2 < 0$, then it is possible to satisfy (2.4).

2. Nevertheless, a wave still cannot exist if the term under the square root in (2.6) is negative because this would lead to a totally complex k_x , which would mean the fields in (2.1) and (2.2) will exponentially grow or decay rather than propagate along the boundary. However, if

$$\varepsilon_1 > 0, \quad \varepsilon'_2 < 0, \quad \text{and} \quad |\varepsilon'_2| > \varepsilon_1, \quad (2.9)$$

then the term under the square root in (2.6) is positive and propagation of a wave at the boundary is assured. This condition (2.9) causes the signs of the terms under the square roots in (2.8) to be negative, but (2.4) will still hold as long as same sign for $\sqrt{-1}$ is chosen for both square roots.

3. If the conditions in (2.9) are met then from (2.6), $k_x > k_0$ and therefore k_z in (2.5) must be complex. According to (2.1) and (2.2), this results in exponential

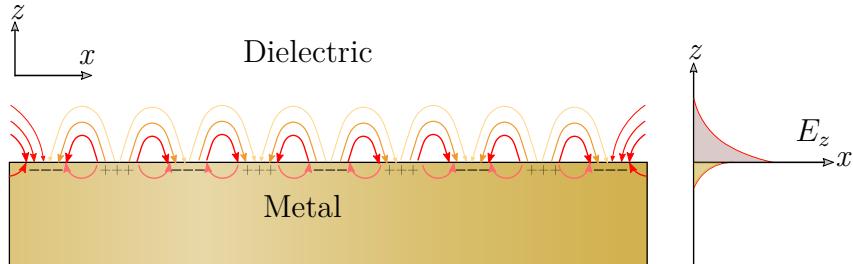


Figure 2.3: Surface plasmon propagation along a dielectric-metal boundary and exponential decay perpendicular to the boundary.

decay of the field away from the boundary in both the positive and negative z-directions as long as $\sqrt{-1} = -j$ is chosen for the square root terms in (2.8). Exponential decay of the plasmon surface wave into the dielectric and metal is illustrated in Fig. 2.3.

4. According to Snell's law, the component of the wavenumber k_x tangential to the boundary is the same in both mediums. If medium 1 is air, the x-component of a plane wave incident upon the boundary at an angle θ from normal is $k_{x1} = k_0 \sin \theta$, which is less than k_0 . However, according to (2.6) and (2.9) surface plasmons cannot exist unless $k_x > k_0$. Therefore, surface plasmons cannot be excited by shining light on a flat metal surface.
5. From (2.7), the velocity of a surface plasmon wave on a planar boundary is:

$$v_{sp} = \frac{\omega}{k'_x} = c \left(\frac{\varepsilon_1 + \varepsilon'_2}{\varepsilon_1 \varepsilon'_2} \right)^{1/2} \quad (2.10)$$

and its wavelength is:

$$\lambda_{sp} = \frac{2\pi}{k'_x} = \left(\frac{\varepsilon_1 + \varepsilon'_2}{\varepsilon_1 \varepsilon'_2} \right)^{1/2} \quad (2.11)$$

6. The exponential decay of a plasmon along its propagation direction is determined by the second term in (2.7). The 'propagation length' of a plasmon wave is the distance $x = L$ at which the wave decays to $1/e$ of its initial value. The plasmon propagation length on a planar surface is therefore:

$$L = \frac{1}{k'_x} = \frac{2\varepsilon''_2}{k_0 \varepsilon'_2} \left(\frac{\varepsilon_1 + \varepsilon'_2}{\varepsilon_1 \varepsilon'_2} \right)^{1/2} \quad (2.12)$$

7. If the conditions in (2.9) hold, the second term on the right hand side in (2.8a)

and (2.8b) are small so, neglecting these terms, perpendicular to the boundary the $1/e$ decay distance into the dielectric is [48]:

$$z_1 = \left| \frac{1}{k'_{z1}} \right| = \frac{1}{k_0} \left| \frac{2(\varepsilon'_2)^2}{k_0 \varepsilon''_2} \left(\frac{\varepsilon_1 + \varepsilon'_2}{\varepsilon_1^2} \right)^{1/2} \right| \quad (2.13)$$

and,

$$z_2 = \left| \frac{1}{k'_{z2}} \right| = \frac{1}{k_0} \left| \frac{2(\varepsilon'_2)^2}{k_0 \varepsilon''_2} \left(\frac{\varepsilon_1 + \varepsilon'_2}{\varepsilon'_2^2} \right)^{1/2} \right| \quad (2.14)$$

into the metal.

8. Power and energy relationships can be found by assuming a value for the magnetic field amplitude and by using Ampere's law to determine the electric field.

The conditions described in (2.9) are met by noble metals in air for the optical and near-infrared ranges in the case of a TM polarized wave. A similar analysis will show that a transverse electric (TE) polarized wave cannot exist at a dielectric-metal boundary.

In practical applications, one should take care in the selection of the metal to be used in a nanoantenna design. Some metals, such as silver, tend to develop an oxidation layer, which can severely decrease propagation length and increase the antenna impedance. For a more detailed discussion concerning the effect of a silver sulfide oxidation layer on a silver substrate plasmon wave, the reader is referred to [43]. Fig. 2.4 shows the propagation length as a function of wavelength for three metals, gold, silver and aluminum [52]. The practitioner is cautioned that although the propagation length of a surface plasmon does increase as frequency decreases, the analysis leading to this figure is based on an idealization of the physical problem. Here, a pure wave propagation condition was assumed in the formulation of equations (2.1) and (2.2). In the practical case, a source such as the feed point of an antenna,

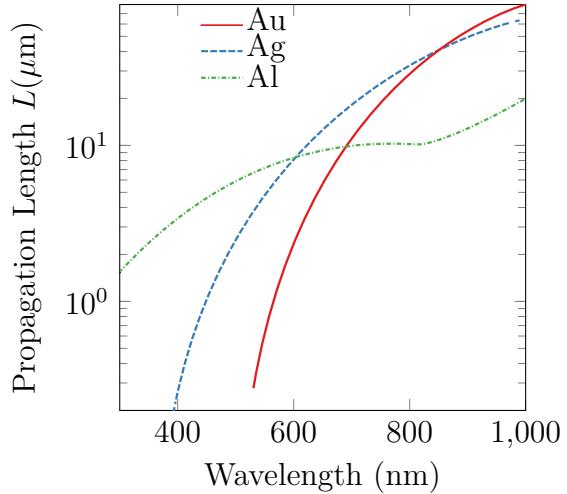


Figure 2.4: Propagation length of a surface plasmon propagating along the interface between a dielectric (refractive index 1.32) and a metal as a function of wavelength calculated for gold (Au), silver (Ag), and aluminum (Al).

must be included in the problem formulation. If the source is included, one sees that as the frequency decreases, less energy is transferred into the surface plasmon wave and more into the space wave; the field that is radiated directly into space from the source point. In the far infrared frequency range, the surface plasmon essentially ceases to exist. Plasmon wave behavior is discussed in more detail in the section of this chapter concerning aperture antennas.

2.4 Quantum effects

The above analysis considers only the classical electromagnetic aspects of propagation on a dielectric metal boundary. However, quantum mechanical effects inherent in metals and dielectrics enter the picture through the permittivity, thereby determining its value as well as the frequency range over which SPPs can propagate. Essentially, quantum processes reveal the frequency range over which the metal has a permittivity with a negative real part and where losses begin to have a serious ef-

fect on wave propagation within that frequency range. In the following, the influence of plasma resonance and atomic collisions on SPP propagation are briefly explored. Although the properties described below are best understood using quantum mechanics, the mathematics below is classical, primarily developed by concatenating harmonic oscillator models. However, the differences in the results of the two theories is small, allowing classical electromagnetic calculations without the necessity of delving into quantum theory. Free electrons can exist near the top of the energy band distribution in a metal. The interaction of these electrons with photons and the long-range Coulomb force of atoms create an electron oscillation known as a plasmon. Taking these effects into account, the dielectric function of metal can be expressed in terms of the Drude model [53]:

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega(\omega - j\nu)} = \left(1 - \frac{\omega_p^2}{\omega^2 + \nu^2}\right) - j \frac{\nu \omega_p^2}{\omega(\omega^2 + \nu^2)} = \varepsilon_r - j\varepsilon_i \quad (2.15)$$

where $\nu = 1/\tau$ is the collision frequency, τ is the scattering time between collisions, and ω_p is the plasma frequency that is expressed as:

$$\omega_p = \sqrt{\frac{Ne^2}{\varepsilon_0 m_e}} \quad (2.16)$$

in which e and m_e are the electron charge and mass respectively and N is the concentration of free electrons. Plasma frequencies for metals are in the visible and ultraviolet ranges. Typical values of plasma and collision frequencies are $\omega_p = 0.23 \times 10^{12}$ Hz and $\nu = 5.51 \times 10^{12}$ Hz for gold and $\omega_p = 0.21 \times 10^{16}$ Hz and $\nu = 4.45 \times 10^{12}$ Hz for silver, however impurities and other factors can affect these numbers so the literature does not have a unique set of values for these parameters. A comprehensive list of plasma and collision frequencies published by a variety of researchers for gold, silver

and other noble metals can be found at [54].

Collisions are primarily between electrons and relatively large lattice vibrations (phonons), so for most metals at room temperature $\nu \ll \omega_p$ [55], which reduces (2.15) to approximately:

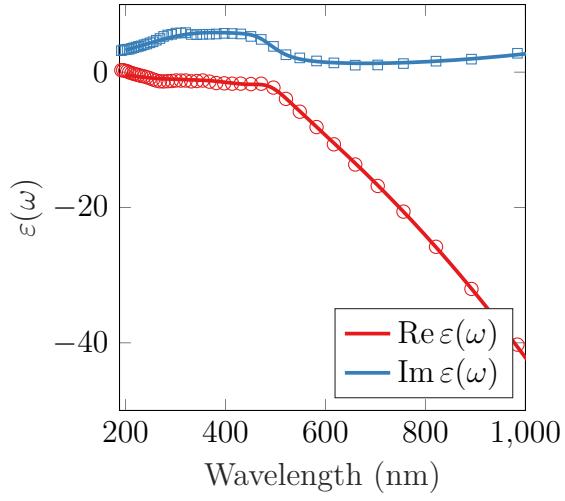
$$\varepsilon(\omega) \simeq 1 - \frac{\omega_p^2}{\omega^2} \quad (2.17)$$

This important expression shows that when $\omega < \omega_p$, then $\varepsilon(\omega) < 0$ which in part satisfies the conditions in (2.9). Therefore, surface plasmon polaritons can only exist below the plasma frequency. Equation (2.17) substituted into (2.6) gives a simplified Drude model for the plasmon wavenumber:

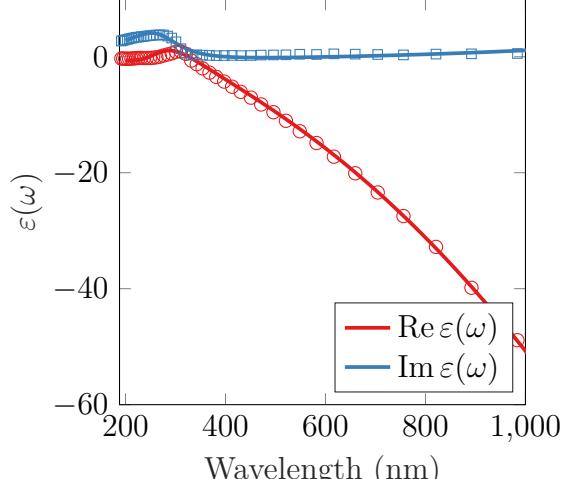
$$k_x \simeq k_1 \left(\frac{\omega^2 - \omega_p^2}{\omega^2 \varepsilon_{r1} + (\omega^2 - \omega_p^2)} \right)^{1/2} \quad (2.18)$$

The Drude model in the form given in (2.15) is widely used in nanoantenna analytical and numerical calculations for determining the permittivity, and therefore the propagation constant, of the plasmon polariton of noble metals. However, this free electron model fails at frequencies higher than about 850 THz [56], due to bound charge effects, and must be modified by incorporating additional terms [55]. This becomes a tedious process but reasonable accuracy can be achieved. Another option, preferred by the authors, is to use measured data [57] with a partial fraction fit [58]. Fig. 2.5 shows the dielectric function for gold and silver over the frequency range from 0.5 eV~120 THz to 6.5 eV~1.57 PHz obtained from measured data via a partial fraction fit. The solid lines are the partial fraction fit for the real part ε' , and the dashed lines are for the imaginary part ε'' , of the dielectric function.

The significance of the data in Fig. 2.5 becomes clearer in Fig. 2.6 where the surface plasmon dispersion curve for frequency versus the propagation k'_x , attenuation



(a)



(b)

Figure 2.5: Dielectric function for (a) Gold and (b) Silver as a function of photon energy $E = hf$ where f is frequency and $h = 6.626 \times 10^{-34}$ kg m²/s is Planck's constant. The solid lines are the partial fraction fit for ϵ' and the dashed line is for ϵ'' . The circles and squares are from measured data originally listed in [1]

k_x'' , and constants at an air-silver boundary are plotted. The lower part of the curve is the non-radiative surface plasmon region followed above by an anomalous dispersion region and above that a Brewster mode radiative region. The slanted dashed line is the free-space light line $k_0 = \omega/c$. The Brewster mode portion of the dispersion

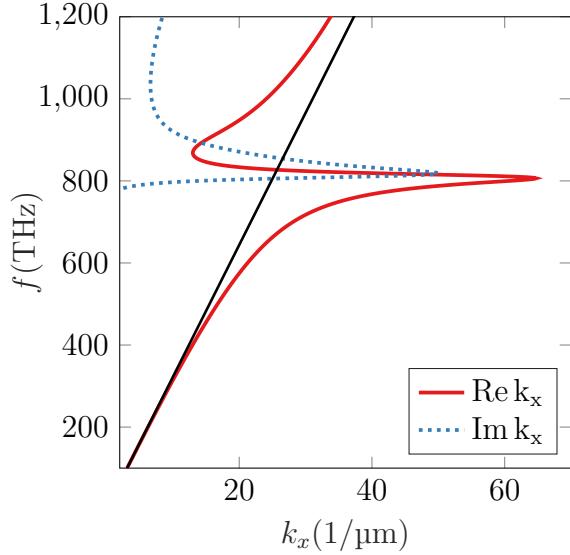


Figure 2.6: SPP dispersion curve for ω versus $\text{Re}(k_x)$ and $\text{Im}(k_x)$ for a glass-silver interface. The lower part of the curve is the non-radiative surface plasmon region which is capped by a high-loss backbending region, and a Brewster mode radiative region above

curve is in the fast wave region to the left of the light line. It is the locus of the values of k_x of the plane wave incident on the boundary at the Brewster angle. These waves do not set up a surface wave, but rather carry their power directly into the metal without reflection. Below the Brewster mode section is a region of anomalous dispersion, often described in the literature as ‘backbending’, which has a group velocity that is virtually zero, and is accompanied by high loss.

The surface plasmon portion of the dispersion curve is of primary importance to nanoantenna design. The plasmon region lies to the right of the light line and therefore, it is a slow wave since the phase velocity here is less than the speed of light. Because surface plasmons have a shorter wavelength than light they are prevented from radiating from a flat planar surface. Of particular significance is the decreasing slope of the dispersion curve, tending toward horizontal near where it

joins the anomalous dispersion segment. In the plasmon region the surface plasmon propagation constant increases dramatically with a small increase in frequency. The horizontal dashed line at 380 nm intersects the light line at approximately $k_0 = 17 \text{ rad}/\mu\text{m}$ while at the same wavelength $k'_x = 21 \text{ rad}/\mu\text{m}$, which means the surface plasmon wavelength can be much less than the free-space wavelength. Therefore, a resonant half-wavelength nano-dipole antenna can be much smaller than a half-wavelength measured in air at the same frequency. As the plasmon wavelength decreases near the anomalous dispersion region, the propagation constant approaches a limiting value. The Drude model provides the estimate for this limiting frequency

$$\omega_{sp} \simeq \omega_p / \sqrt{1 + \varepsilon_{r1}}, \quad (2.19)$$

obtained by setting the denominator in (2.18) equal to zero, which is equivalent to assuming the propagation constant in (2.18) approaches infinity. This is not what happens to the propagation constant, as can be seen in Fig. 2.6 where real data is used, but it does provide a reasonable estimate of the limiting frequency. nanoantennas must be designed to operate below this frequency, thereby avoiding a group velocity approaching zero and dramatically increased losses.

Although several key aspects of wave propagation on nano-structures have been presented here, all analysis has been performed assuming propagation is on a surface between two half spaces. However, most nanoantennas have air above and are etched in a noble metal, such as gold, on a dielectric substrate, such as silicon dioxide. The metal antenna, therefore lies between two different materials. nanoantennas are typically excited at a corner or edge where both upper and lower surfaces are exposed to the incoming electromagnetic field. Because the plasmon propagation constant (2.7) is a function of the permittivity in the regions above and below an interface, it

will be helpful to understand how different phase velocities (2.10) and wavelengths (2.11) on the two sides of a nanoantenna will affect its performance. This issue is briefly addressed in the following paragraphs.

2.5 Two Boundary Structures

Surface plasmon polaritons on a metal film have properties that do not exist on an interface between metal-dielectric half spaces. To analyze the mode configuration on a metal strip of thickness t , consider the configuration shown in Fig. 2.7 where the dielectrics are assumed to extend from the surface of the metal to infinity and possess different permittivities, ε_1 and ε_2 . The permittivity of the metal is ε_m and all three regions have the permeability of free-space. The waves in each region are assumed to be TM polarized with a magnetic field component in the y -direction in each region given by:

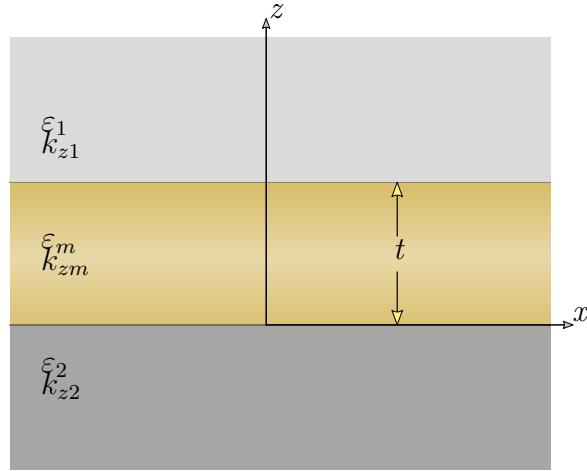


Figure 2.7: Thin metallic film between two dielectric regions with different permittivities.

$$\mathbf{H}_1 = \hat{\mathbf{y}} H_{y1} e^{-A_{z1}z - jk_x x}, \quad \text{dielectric region } 1(z \geq t) \quad (2.20a)$$

$$\mathbf{H}_m = \hat{\mathbf{y}} \left(H_{ya} e^{+A_{zm}z} + H_{yb} e^{-A_{zm}z} \right) e^{-jk_x x}, \quad \text{metal region } m(0 \leq z \leq t) \quad (2.20b)$$

$$\mathbf{H}_2 = \hat{\mathbf{y}} H_{y2} e^{-A_{z3}z - jk_x x}, \quad \text{dielectric region } 2(z \leq 0) \quad (2.20c)$$

where the dispersion relations for the three regions are,

$$A_{zi}^2 = -k_{zi}^2 = k_x^2 - k_0^2 \varepsilon_i, \quad \text{for } i = 1, 2, m \quad (2.21)$$

and the boundary conditions satisfied by \mathbf{H}_m at each interface are:

$$H_{ym} = H_{yi} \quad (2.22a)$$

$$\frac{1}{\varepsilon_m} \frac{\partial H_{ym}}{\partial z} = \frac{1}{\varepsilon_i} \frac{\partial H_{yi}}{\partial z} \quad (2.22b)$$

where $i = 1, 2$. Each of these conditions are applied to (2.20) at each boundary yielding a set of four homogeneous linear equations which can be combined to produce:

$$\frac{H_{yb}}{H_{ya}} = \frac{\left(\frac{\varepsilon_2 A_{zm}}{\varepsilon_m A_{z2}} - 1 \right)}{\left(\frac{\varepsilon_2 A_{zm}}{\varepsilon_m A_{z2}} + 1 \right)} \quad (2.23a)$$

$$\frac{H_{yb} e^{-2A_{zm}t}}{H_{ya}} = \frac{\left(\frac{\varepsilon_1 A_{zm}}{\varepsilon_m A_{z1}} + 1 \right)}{\left(\frac{\varepsilon_1 A_{zm}}{\varepsilon_m A_{z1}} - 1 \right)} \quad (2.23b)$$

The equations in (2.23) are equated to produce the three dispersion relation:

$$\left(\frac{\varepsilon_m A_{z1}}{\varepsilon_1 A_{zm}} + 1 \right) \left(\frac{\varepsilon_m A_{z2}}{\varepsilon_2 A_{zm}} + 1 \right) = \left(\frac{\varepsilon_m A_{z1}}{\varepsilon_1 A_{zm}} - 1 \right) \left(\frac{\varepsilon_m A_{z2}}{\varepsilon_2 A_{zm}} - 1 \right) e^{-2A_{zm}t} \quad (2.24)$$

for the metal layer sandwiched between two different dielectrics. Equation (2.24) can be verified by allowing the metal thickness to become large, $A_{zm}t \rightarrow \infty$, in which case the right hand side goes to zero. This yields a pair of equations:

$$\frac{\varepsilon_m A_{z1}}{\varepsilon_1 A_{zm}} + 1 = 0 \quad (2.25a)$$

$$\frac{\varepsilon_m A_{z2}}{\varepsilon_2 A_{zm}} + 1 = 0, \quad (2.25b)$$

recognized from (2.4) to be the dispersion relations for surface plasmon polaritons at the boundaries between two individual dielectric-metal half-spaces.

If ε_1 and ε_2 are positive and $\varepsilon_m < 0$, the right hand side of (2.24) is positive, which means the left hand side must also be positive. This is possible if, $\left(\frac{\varepsilon_m A_{z1}}{\varepsilon_1 A_{zm}} + 1\right)$ and $\left(\frac{\varepsilon_m A_{z2}}{\varepsilon_2 A_{zm}} + 1\right)$ are both positive or both negative. Under the assumption that both are negative, that $\varepsilon_1 > \varepsilon_2$, and $|\varepsilon_m| > \varepsilon_1$ the characteristic equation (2.24) becomes [59],

$$A_{zm}t = \coth^{-1}\left(\frac{|\varepsilon_m| A_{z1}}{\varepsilon_1 A_{zm}}\right) + \coth^{-1}\left(\frac{|\varepsilon_m| A_{z2}}{\varepsilon_2 A_{zm}}\right). \quad (2.26)$$

Similarly, assuming that both expressions in brackets on the left hand side of (2.24) are positive and $|\varepsilon_m| < \frac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 - \varepsilon_2}$ the characteristic equation becomes [59],

$$A_{zm}t = \tanh^{-1}\left(\frac{|\varepsilon_m| A_{z1}}{\varepsilon_1 A_{zm}}\right) + \tanh^{-1}\left(\frac{|\varepsilon_m| A_{z2}}{\varepsilon_2 A_{zm}}\right). \quad (2.27)$$

Equations (2.21) together with (2.26) or (2.27) can be used to solve for the wavenumbers in the even and odd mode cases, referring respectively to the symmetric or asymmetric form of the tangential (z-directed) component of the electric field about the center of the metal layer [60].

When the metal layer is thick, the waves on the two sides of the metal slab do not interact, as indicated in (2.25). However, as the slab becomes thinner the

electromagnetic fields on the two sides do interact and the frequency splits into a low frequency even mode (2.26) and a higher frequency odd mode (2.27). Although the tangential electric field is not entirely symmetric in the metal region when $\varepsilon_1 \neq \varepsilon_2$, more of the field lies inside the metal in the even mode case (2.26) than it does in the basically asymmetric odd mode case (2.27). As the metal layer becomes thinner, the damping of the odd mode decreases, approximately as the square of the thickness, allowing this mode to travel a greater distance than a plasmon polariton on the interface between two half spaces. However, the basically symmetric mode damping increases with decreasing thickness, allowing propagation distances one or two orders of magnitude greater than those of thick metal construction [61]. The physical reason attributed to this phenomena is that in the asymmetric case, where the null is in the center of the metal, more of the field resides outside as the thickness of the metal decreases therefore, lessening the presence of the tangential electric field in the metal thereby reducing Joule heat which in turn decreases the electron collision rate resulting in less damping of the wave. This analysis suggests that the efficiency of an optical antenna can be improved by decreasing the thickness of the metallic material with which it is constructed and operating in the higher odd mode frequency range.

When the metal width is finite and the environment is symmetric ($\varepsilon_1 = \varepsilon_2$), there are four fundamental modes and a number of higher order modes. These modes can be classified according to the cross-sectional width and thickness, similar to a rectangular waveguide and will become successively cut off as the thickness decreases leaving one Gaussian like mode. Efficient optical fiber coupling to this plasmonic mode in a metal guide has been demonstrated [62], raising the possibility of similar coupling between optical antennas and metal strip plasmonic waveguides designed with the appropriate width and thickness so as to operate in this particular mode. Closer to the nanoantenna case, in an asymmetric environment ($\varepsilon_1 \neq \varepsilon_2$)

there is no purely TM mode. It has been shown that modes in this case can change their symmetry properties with changes in both transverse directions, width and thickness, and that all modes show a cutoff height that increases both with decreasing width and increasing dielectric mismatch between the sub- and superstrate [62, 63]. Unfortunately, this includes air-metal-glass configurations commonly used in the design of optical antennas and waveguides. Thus the complicated spatial profiles shown in modes in an asymmetric environment prohibit efficient excitation techniques [50, 64].

In this section it has been shown that in the optical frequency range electromagnetic wave propagation, which is via a surface plasmon polariton, can take place on an air-dielectric boundary if one of the two materials has a dielectric constant with a negative real part obeying the conditions in (2.9). The dispersion equation for this wave is given in (2.6) and presented graphically in Fig. 2.6, which shows that a surface plasmon is a slow wave, i.e. slower than the speed of light in the dielectric medium. The Drude model, which is relatively accurate below, and not too close to, the plasma frequency ω_p and useful for analytical calculations, was given in (2.15). This model, or its approximation in (2.17), is commonly used to obtain approximate velocity (2.10), wavelength (2.11), propagation distance (2.12), and exponential decay distance away from the boundary (2.13) and (2.14) of the plasmon wave. It also provides an estimate of maximum frequency (2.19) at which a plasmon wave can propagate. Although Fig. 2.6 shows that the surface plasmon wavelength can be much less than the free-space wavelength, close to the maximum frequency the plasmon wave will experience severe attenuation.

Because optical antennas are operated in a frequency range which is at the overlapping boundary between electromagnetic and quantum theories, in the paragraphs above, some of the quantum justification for the unusual behavior of materials in

the near infrared and optical domains has been presented. This discussion was then followed by an asymmetric two boundary case development of the dispersion equations modeling a typical optical antenna structure in cross-section, showing that the interaction between the plasmon waves on the two boundaries breaks into symmetric and asymmetric modes, (2.26) and (2.27). The symmetric mode is preferred when coupling to another device and the asymmetric mode is preferred for long distance propagation in a plasmon waveguide. This section then concluded with a discussion of the finite width metal guide that has been shown to have a complicated mode structure, hampering efforts to obtain a mathematical expression for impedance matching. Current attempts at obtaining a mathematical model and along with design methods that improve impedance matching and enhance optical antenna radiation will be covered in the individual antenna discussions that follow.

2.6 Design of Optical Antennas

The plasmonic nature of nanoantenna operation prevents the designer from describing antenna performance with formulas that have been developed over many decades at microwave and lower frequencies. Dielectric properties of metals are only one factor preventing a direct correspondence between established antenna theory and actual optical antenna operation. A traditional antenna concept that the wave vector for the current is the same as the free-space wave vector must be abandoned, dispersion effects must be accounted for and losses not generally expected in a microwave frequency ‘perfect conductor’ become dependent on the size and shape of the antenna. The optical antenna, although not a traditional perfect conductor, cannot be analyzed as though it is a pure dielectric rod as would be the case for an optical fiber. But even if an optical antenna could be modeled as a pure dielectric, the tips of a rod represent the famous unsolved dielectric wedge problem. As described

above, the fast wave current on a perfect conductor must be replaced by a slow wave plasmon current tightly coupled to the antenna surface. Radiation on an optical dipole still occurs at the tips of the rods and can still be viewed as current induced. The primary difficulty that must be faced when attempting an analytical analysis is that for practical reasons the design requires placing the antenna on an interface between a dielectric below, such as a silicon dioxide substrate, and air above. Although numerical techniques can be used to accurately analyze the characteristics of the structure, similar to microstrip patch antennas, no exact analytical methods are available. Analytical approximations and numerical attempts to obtain the basic characteristics of an optical antenna, the resonant frequency, input impedance, gain, directivity and efficiency, are presented in this section.

2.6.1 Dipole and Patch Antennas

Size and shape can affect the design frequency of an optical antenna in ways not typically expected in microwave frequency antenna engineering. For example a rectangular microstrip patch is expected to resonate when the incident field is polarized in the direction of the $\lambda/2$ dimension of the patch, while the transverse dimension is flexibly left to something greater or less than $\lambda/2$. However, as shown in Fig. 2.9 both the width and length of a metal plate must be considered in designing an optical antenna. A narrow nanodipole resonating at a particular frequency, as shown in Fig. 2.8, does not maintain resonance when widened. However, the first resonance can be regained by changing both the length and width of the dipole as shown in Fig. 2.9c. The mechanism causing this phenomena has to do with the manner in which surface plasmons are excited. The incident wave with a free-space wavenumber transfers energy into the plasmon wave having a much larger wavenumber at locations where the interaction between the incident wave and the

antenna produce the largest concentration of higher order modes, which will couple energy into the plasmon mode. This interaction is primarily seen on the corners of the dipole in Fig. 2.9c. Similar to plane waves in a waveguide, plasmon waves fan out from the corners taking a circuitous route bouncing from the edges of the plate before phase matching produces a resonance condition. Further complicating the picture is the chemical potential and the ‘lighting rod’ effect whereby opposite charges form a high concentration of the field across the antenna center gap. However, plasmons in the narrower dipole, Fig. 2.9b, follow a shorter, more direct route to resonance than does the plasmon wave on the wider dipole Fig. 2.9c thereby experiencing less attenuation and ultimately creating a region of higher field enhancement in the gap than does the wide dipole. Fig. 2.9a shows that as the dipole widens the resonant frequency shifts and the enhancement decreases. Enhancement is defined as the ratio of the total to the incident electric field in the gap region, although in some publications this ratio is squared and therefore, described as intensity enhancement.

The behavior of the narrower dipole shown in Fig. 2.9b is more closely aligned with what one would expect at microwave frequencies whereby increasing the length of each nanorod in plasmon half-wavelength intervals will produce successive reso-

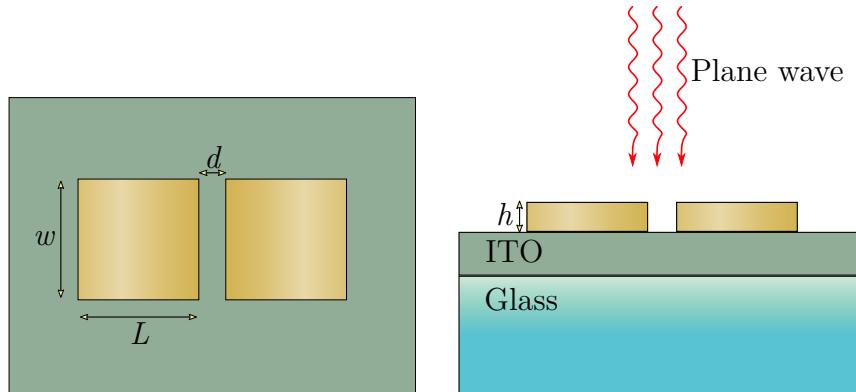
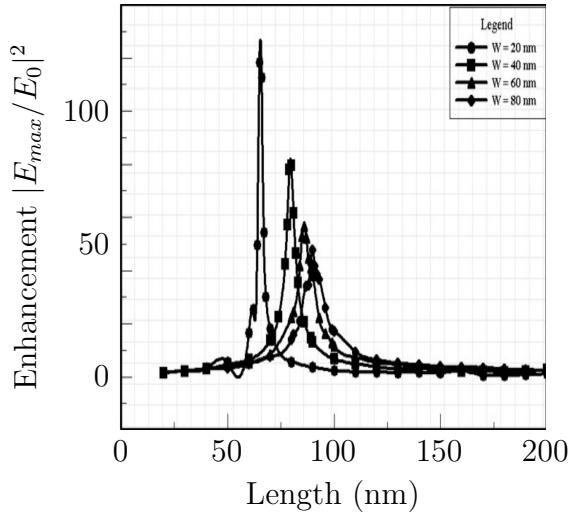
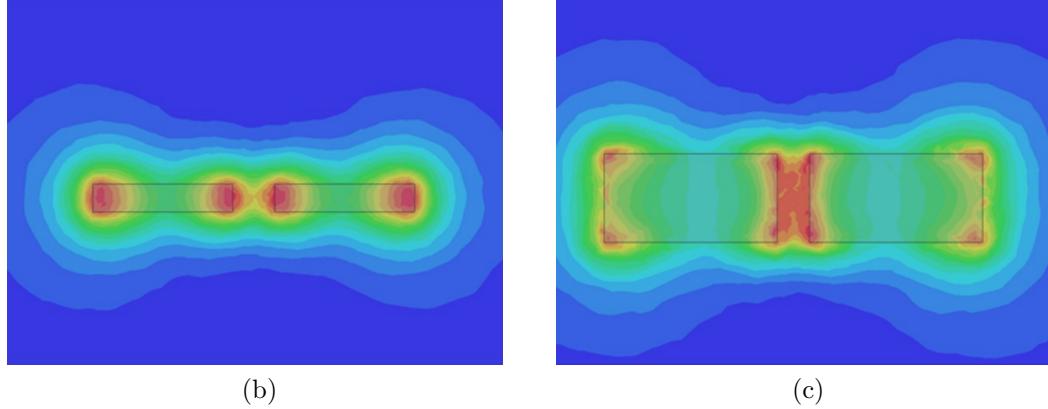


Figure 2.8: A gold dipole residing over a glass substrate.



(a)



(b)

(c)

Figure 2.9: (a) Maximum enhancement of a gold nanodipole excited at 550 nm (b) narrow and (c) wide profile. A narrow structure does not maintain resonance when widened without also changing its length.

nance and antiresonance in the gap input impedance. Notice that the total length of the dipole is a full plasmon wavelength λ_p plus the gap separation distance, as opposed to the typical $\lambda_0/2$ dipole first resonance of a perfectly conducting microwave antenna with a negligible gap width. In terms of plasmon wavelengths, a first resonance does occur in an isolated $\lambda_p/2$ nanorod or a vertical $\lambda_p/4$ nanorod on a metal substrate [65].

Although an exact determination of the plasmonic wavelength in a dielectric nanorod is not mathematically feasible, an effective wavelength λ_{eff} based on the assumption that the antenna is a thin dielectric cylinder operating in the TM_0 cylindrical waveguide mode has been derived in [66]. The antenna is immersed in a material with dielectric constant ε_s , and a Drude dielectric function is used to describe the metal rod material. The apparent increase in the antenna length at the rod ends is accounted for by an additional reactance term. This scaling law is:

$$\lambda_{eff} = n_1 + n_2 \left(\frac{\lambda}{\lambda_p} \right) \quad (2.28)$$

where λ is the wavelength of the external region, λ_p is the metal plasma wavelength, and n_1 , n_2 coefficients with dimensions of length that depend on antenna geometry and static dielectric properties, are

$$n_1 = 2\pi R \left[13.74 - 0.12 \frac{\varepsilon_\infty + 141.04 \varepsilon_s}{\varepsilon_s} - 2\pi \right] \quad (2.29a)$$

$$n_2 = 0.24 \pi R \frac{\sqrt{\varepsilon_\infty + 141.04 \varepsilon_s}}{\varepsilon_s}. \quad (2.29b)$$

Here R is the radius of the cylinder, and ε_∞ is the dielectric constant correction in the Drude formula for $\omega \gg \omega_p$. For gold $\varepsilon_\infty \simeq 11$, $\lambda_p = 138$ nm and for silver $\varepsilon_\infty \simeq 3.5$, $\lambda_p = 135$ nm [66].

In the case of an optical patch or dipole antenna it is necessary to account for a phase shift acquired by the surface plasmon polariton upon reflection at rod, strip, or gap terminations. The resonance wavelength λ of metal strip resonators of thickness t and width w are determined approximately by [67]:

$$w \frac{2\pi}{\lambda} n_{slow} = m\pi - \phi \quad (2.30)$$

where n_{slow} is the real part of the mode index of surface plasmon polaritons propagating in a metal film with the same thickness t as the strip, $m = 1, 2, 3, \dots$ is the order of the resonance, and ϕ is the phase of the reflection coefficient at strip terminations. For a symmetric structure where $\varepsilon_d = \varepsilon_1 = \varepsilon_2$, once t and ε_m are selected and the phase shift ϕ is determined, n_{slow} can be obtained from (2.21) and (2.25) or for thin strips, one can use the approximation [68]:

$$n_{slow} \simeq \sqrt{n_d^2 + \frac{4 n_d^4}{k_0^2 t^2 n_m^4}} \quad (2.31)$$

where n_d and n_m are the indices of refraction of the dielectric and metal and $k_0 = 2\pi/\lambda$. The wavelength of the slow surface plasmon polariton is then given by $\lambda_{slow} = \lambda/n_{slow}$.

Analytical models are preferable because clear trends in antenna performance can be seen by adjusting mathematical parameters that represent physical quantities such as the antenna width or length and the excitation frequency. On the other hand, numerical techniques can provide both the accuracy and flexibility needed to model complex antenna structures. However, purely mathematical solutions can become clouded with long complex expressions and special functions while a purely numerical analysis provided by the powerful commercial codes that have become available these last few years, while furnishing useful visual data in terms of graphs and charts, do not always provide a way to understand the multifaceted interaction between the variables of an antenna system. Recently a compromise approach for optical antennas has been advanced, advocated primarily by Engheta and Alù [69, 70, 71, 72], whereby the antenna and field excitation are replaced by an equivalent lumped circuit model based on numerical analysis data. The basic model, shown in Fig. 2.10, is centered on a Thévenin equivalent circuit for the antenna with a capacitance accounting for a

non-negligible gap impedance Z_g along with the intrinsic impedance Z_a of the dipole. The parallel combination of these two impedances forms the input impedance of the circuit. The input impedance is calculated, by driving the antenna at the gap with an arbitrary source voltage V_g and calculating, with full-wave simulations, the displacement current I_g flowing across the arms at the terminals in the region of the gap $Z_{in} = V_g/I_g$.

The intrinsic antenna impedance Z_a is extracted from the input impedance by first taking the parallel combination of the gap and load impedances according to:

$$Z_{in} = \frac{1}{1/Z_a + 1/Z_g}, \quad Z_g = \frac{1}{j\omega C}, \quad \text{where } C = \varepsilon_0 S/g \quad (2.32)$$

where S and g are respectively the gap cross-sectional area and gap height. Setting $Z_a = R_a + jX_a$ and $Z_{in} = R_0 + jX_0$, (2.32) is rearranged to give:

$$R_a = \frac{R_0}{1 + \omega C (2X_0 + \omega C (R_0^2 + X_0^2))} \quad (2.33a)$$

$$X_a = \frac{X_0 + \omega C (R_0^2 + X_0^2)}{1 + \omega C (2X_0 + \omega C (R_0^2 + X_0^2))}. \quad (2.33b)$$

Since full-wave simulations have provided the Z_{in} components R_0 and X_0 , the dipole intrinsic impedance is determined mathematically from (2.33). The intrinsic impedance Z_a , which is unaffected by antenna loading either by a transmission line or by altering the gap capacitance, is now completely determined.

The antenna is resonant when the input reactance $X_0 = 0$ which from (2.33b) is:

$$\omega_0 = \frac{X_a}{C(R_a^2 + X_a^2)} \quad (2.34)$$

The ‘open circuit’ or first resonance has been shown to have a very low value, whereas

the ‘short circuit’ or antiresonance has a high impedance, on the order of kilo-ohms. The feed line or other loading conditions will determine which operating frequency is selected. In the event of loading, the capacitance becomes $C = \varepsilon_L S/g$, the new resistance and reactance terms in the input impedance $Z_{in} = R_{in} + jX_{in}$ are again found numerically and the equivalent dielectric constant ε_L can be calculated from (2.33b). Extra circuit elements can be added to account for the transmission feed line or a quantum radiator such as is the case in molecular spectroscopy, or a different circuit can be created for single quantum radiators without a gap [72]. Efficiency is an important measure used to characterize antenna performance. The overall antenna efficiency can be broken down into the product of several measures of efficiency, the most important of which are the radiation efficiency and the reflection efficiency, $\eta = \eta_{rad}\eta_{ref}$, where the maximum value of each efficiency is one. The reflection efficiency determines how well the transmission feed line characteristic impedance is matched to the antenna input impedance. Its value, given in terms of the transmission line reflection coefficient Γ , is $\eta_{ref} = 1 - |\Gamma|^2$ where $|\Gamma| \leq 1$. The radiation efficiency is ratio of the total power radiated P_{rad} to the power received P_{in} by the antenna. The input power is assumed to be the sum of the radiated power and the power

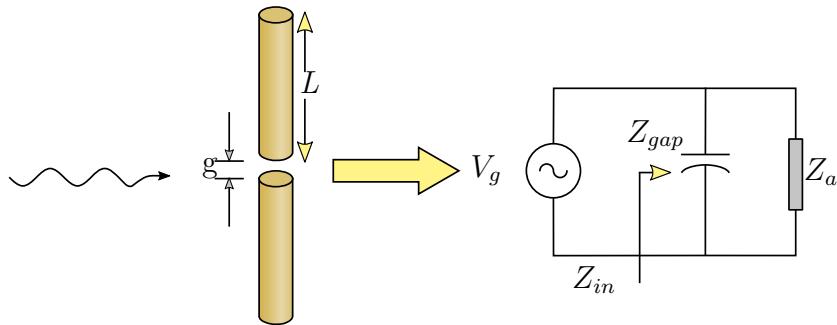


Figure 2.10: Optical antenna with equivalent circuit model. The driving voltage could be an incident electromagnetic field, a transmission line connected to the antenna, or a quantum emitter.

losses on the antenna. Provided the antenna is fed at the antenna maximum current point, which is most often the case with optical antennas operating at or below the lowest resonant frequency. At the first antiresonance, the radiation efficiency can be expressed in terms the radiation resistance R_{rad} and the ohmic loss resistance R_L experienced by the current flow in the antenna elements. The radiation efficiency is therefore:

$$\eta_{rad} = \frac{R_{rad}}{R_{rad} + R_{in} \sin^2(\pi L_{eff}/\lambda_{eff})}; \quad R_{rad} = 2P_{rad}/I_{max}^2. \quad (2.35)$$

The ohmic loss resistance R_{in} is the real part of the input impedance. The optical dipole radiation resistance can be determined analytically by first hypothesizing the current at resonance. Taking into account the effective length and wavelength of an optical antenna, L_{eff} and λ_{eff} respectively which can be calculated using (2.28), the standard microwave expression for a dipole current is modified to become [70],

$$I(z) = \frac{I_0 \sin \left[\pi \frac{L_{eff} - 2|z|}{\lambda_{eff}} \right]}{\sin \left(\frac{\pi L_{eff}}{\lambda_{eff}} \right)} \quad (2.36)$$

where I_0 is the numerical displacement current at the feed point $z = 0$. This current (2.36) is used to find an analytical expression for the power radiated by the optical dipole P_{rad} which is then substituted into (2.35) to find the efficiency.

Antenna directivity defined as $D_0 = (\text{time average power density maximized with angle})/(\text{average total power radiated through a sphere})$, can again be analytically calculated with the formulas above as can gain which is the product of the efficiency times the directivity, $G_0 = \eta_{rad} D_0$. Keep in mind that this exercise has been a combination of numerical and analytical calculations, forming a hybrid approach

that seems best suited for understanding complex interactions as well as for overall engineering optical antenna design. Although the example of a dipole has been used here, many other structures have been successfully investigated using this equivalent technique [71, 72]. For design data for the dipole based on measurements the reader is referred to references [73, 74, 75].

2.6.2 Bowtie Antenna

Compared to a dipole antenna, the bowtie antenna has the advantage of broadband operation yet it is a simple design. The feed point of a bowtie antenna is a gap at the vertex of two tip to tip apposal triangular electrically conducting arms. If extended to infinity while the angles of the triangle vertices remain unchanged, this antenna would be frequency independent. When the incident field polarization is perpendicular to the gap, the antenna can be driven into resonance. Fig. 2.11 shows the intensity distribution for a 520 nm resonant bowtie design made out of gold on a SiO₂ substrate and excited by a normally incident plane wave. The numerical simulation in Fig. 2.11a shows that a high field intensity distribution occurs not only at corners and in the gap region but also along each of the sides, likely due to the sharp edge design. In Fig. 2.11b a plot of the electric field vectors immediately above the surface of antenna indicate the largest field components are just above the gap region but tend to decrease in amplitude as they spread out and terminate at the wider ends of the antenna arms where a much lower intensity is seen in Fig. 2.11a. The intensity of the field in the bowtie gap has been shown to be strongly dependent upon the gap width [73]. For the design presented in [73], starting on the order of 50 nm the resonant intensity climbs exponentially as the gap separation narrows, however as the gap separation widens the intensity tends to level out at around 100 nm. Although very little work has been carried out concerning mathematical design criteria

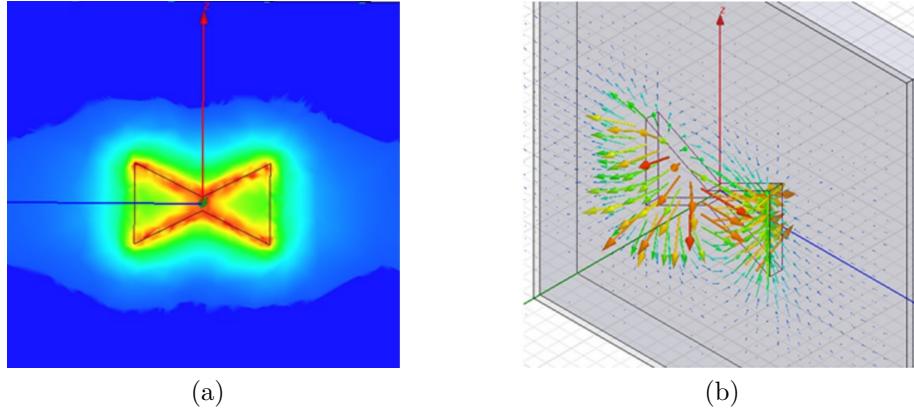


Figure 2.11: Bowtie antenna with (a) highest field intensity shown in red around the edges and corners of the triangular arms and (b) electric field vectors where the largest amplitude field is displayed in red occurs in the gap between the two arms.

for the construction of on-surface optical antennas, optimal design dimensions can be obtained through published data gathered in experiments. For optical frequency design data based on measurements for the bowtie antenna the reader is referred to reference [74]. Studies have also been carried out to determine optimum bow angle, the outside angle formed by the edges of the two apposal arms of a bowtie antenna. It has been reported that the strongest enhancement can be obtained with a bow angle of 90° [74]. Unlike microstrip antennas printed on a thin substrate with a metal backing focusing radiation into the air region above, optical antennas are a single metal radiator lying on a dielectric-air interface. There can be no ground plane below because there are no perfect conductors at optical frequencies. Although radiation is in both directions, most of the energy radiated from an optical antenna tends to couple into the higher density substrate. In the microwave case a TM_0 mode surface wave can be launched into the substrate because this mode has no cutoff wavelength, but the fundamental mode in a typical microwave patch antenna is not conducive to launching TM modes. As long as the substrate is thin, a microwave patch an-

tenna suffers little substrate induced loss. As the substrate thickens, energy from the microwave patch antenna is coupled into surface wave modes, which seriously degrades the efficiency of an antenna. However, an optical antenna radiates in both directions regardless of the substrate thickness, making it in any case less efficient than its microwave counterpart. One measurement study carried out in the infrared range [74] concluded that the dipole and bowtie efficiencies are respectively 20 % and 30 % whereas a typical microstrip patch antenna has an efficiency of 60 %. A similar conclusion was reached in a more recent study [72] that included the optical dipole, bowtie, and dimer constructions. A dimer, which has two pancake shaped arms, has an efficiency level close to the bowtie design. Numerical investigations of the optical Yagi-Uda design show a strong emission into the substrate and a much smaller emission lobe into the air side of the surface [76] [77]. Although most of the electromagnetic radiation is emitted into the critical angle below, the above surface emission still shows a strong directivity.

2.6.3 Yagi-Uda Antenna

The dipole and bowtie nanoantennas described above are most often used in applications where a wide beamwidth or broadband transmission is the primary objective. However as nanotechnology progresses, achieving highly directional beams in the optical regime will be necessary in order to, for instance, transmit signals from nanocircuits to a receiver above the surface with a minimum power load on the electronic system. Another significant application is the possibility of enhancing and directing the radiation from a nano-emitter, which will be discussed in the *Applications* section below. At the microwave level the Yagi-Uda antenna shown in Fig. 2.12 has proven to be highly directional for radiation of radio waves yet simplistic in construction. One would expect that basically similar design principles can be used

to obtain directionality with an optical Yagi-Uda design. Over the last few years, this has been shown to be the case primarily due to the fact that the elements of the Yagi antenna are nanorods, the properties of which have been the subject of extensive study by the optics community over the last thirty years. The essential Yagi-Uda

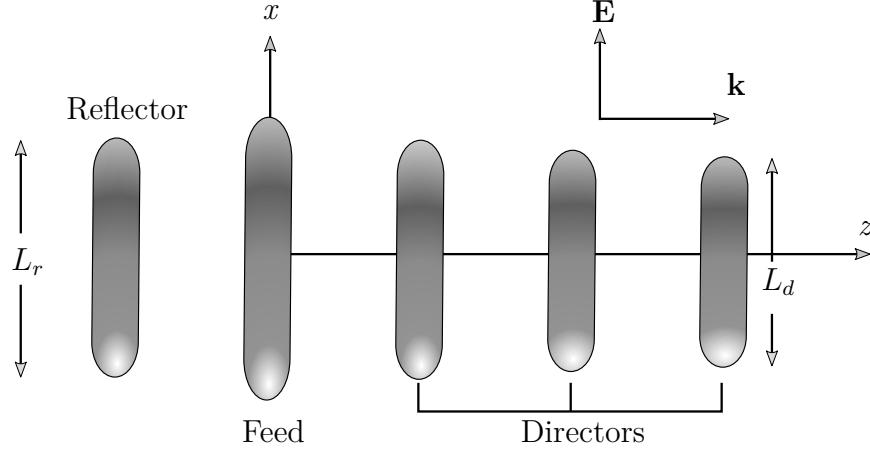


Figure 2.12: Yagi-Uda optical antenna constructed with nanorods.

design consists of a resonant driven element flanked on one side by a longer passive reflector element and on the other by a series of shorter director elements, all of which lie in the same plane. Researchers have studied a variety of element types for the Yagi, including spheres and prolate spheroids, but low efficiency and difficulties in achieving smooth surfaces and precise positioning on the nano level has focused attention on the classical cylindrical rod design. In addition to surface smoothness and the precise rod length and positioning needed for optimum array performance, other difficulties encountered in the optical regime are the loss of energy coupled into the substrate, the difference in wavelength between free-space and the metallic rods, and field interaction with the air-substrate boundary causing a phase difference between surface plasmons on the two sides of the antenna. Naturally these effects can be

modeled by pure numerical calculations but preventing unwanted consequences such as the substrate energy loss are still left open for future research. However detailed design rules have been developed [76] for the optical Yagi. As a rough estimate high directivity can be obtained with separation distances of about 0.25λ between the feed and the reflector and about 0.3λ between the feed and the director and between each of the director elements [77]. The length of the feed element is the effective resonant wavelength λ_{eff} of the antenna rods which is related to the incident free-space wavelength λ by a simple relation given in (2.28) above with an accompanying discussion.

A scanning near-field optical microscope (SNOM) has been used to simultaneously image the amplitude and phase of the normal electric field component on a working Yagi-Uda nanoantenna [78]. This data was processed to produce a time evolution animation of the fields of the antenna during reception, providing an unusual opportunity to check time domain numerical simulations of the received fields. These measurements showed that illumination of the antenna from the forward direction resulted in constructive interference of scattered light by the antenna elements which leads to a strong field enhancement in the feed element. Measurement data taken when illumination is from the rear of the antenna reveal that the destructive interference by the feed element suppresses strong fields.

2.6.4 Log-Periodic Antenna

To date, most theoretical and experimental studies on directional optical antennas have focused on the Yagi-Uda design, shown in Fig. 2.12, which provides good directivity for a specific design frequency with a limited bandwidth. A possibility of improving both bandwidth and directivity may be met with a log-periodic antenna design. The name is derived from a progressive spacing between the elements of the

antenna based on a logarithmic scale. A number of log-periodic design schemes have been employed at microwave frequencies. At optical frequencies several graded size and spacing designs have been proposed with elements varying in shape from spheres and ellipses to the classical elongated rod. Due to difficulties in creating precise size and shapes at the nano level most implementations are only approximations of the true log-periodic requirement.

In a log-periodic antenna arrangement [79], the arm lengths l_n , spacing between arms R_n and rod diameters d_n , increase logarithmically as defined by the inverse of the geometric ratio τ as given by:

$$\frac{1}{\tau} = \frac{l_{n+1}}{l_n} = \frac{R_{n+1}}{R_n} = \frac{d_n}{d_{n+1}}. \quad (2.37)$$

Another parameter associated with the array, but independent of the geometric ratio, is the scaling factor. The scaling factor is often expressed normalized by the element length and as such it is given by $\sigma = d_n/2l_n$. The half angle at the antenna apex is determined by the parameters τ and σ according to $A = \tan^{-1} [(1 - \tau)/4\sigma]$.

In one study [80], measurements were carried out on an optical log-periodic antenna with gold elements on a glass substrate strictly following the design criteria above. However unlike other optical array designs, a gap was placed in the middle of each arm in order to enhance the field produced by plasmonic action. It was observed that the directionality of the antenna reaches a maximum with $N = 10$ elements but the optimum field enhancement value of $|E_{FB}|^2$ for the forward beam electric field is obtained between $N = 6$ and $N = 10$. A decrease of the field enhancement values, defined as $|E_{total}|^2/|E_{inc}|^2$ with increasing numbers of elements is associated with increasing plasmonic losses incurred in the addition of elements. Adding a gap did not affect the antenna patterns, however a significant increase in beam intensity was

observed. As with other on-surface plasmonic antennas, a significant portion of the radiated power is coupled into the substrate.

One of the drawbacks of the log-periodic design is that the currents in the optical version have the same phase in each element. In addition, the elements are closely spaced producing a phase progression of the current in the direction of the longer elements. This produces an end-fire beam in the direction of the longer elements and interference effects in the pattern. The standard design for a log-periodic antenna calls for crisscrossing the feed between adjacent elements thereby adding a 180° phase shift to the terminal of each element. Since the shorter elements are spaced closer together and opposite in phase, very little energy is radiated from them and interference effects are minimal. The radiation pattern in this crisscross case tends to be toward the shorter elements [79]. In the previous paragraph, the design calling for dipoles rather than solid rods appears to be a step in the right direction. The plasmonics of optical frequency materials and construction methods on the nano level will determine the efficacy of adapting the standard microwave design where alternate dipoles are connected.

2.6.5 Purcell factor

Light emission from an optical quantum emitter such as a quantum dot or a nanocrystal can be enhanced when it is in close proximity to an intense electromagnetic source. This effect was first discovered at radio frequency by E. M. Purcell, when he observed an increase in the probability of spontaneous emission of an emitter placed in a resonator [81]. However, controlling the degree of enhancement of a quantum emitter remains a major challenge. Optical microcavities or microresonators such as optical nanoantennas, generally used for emission enhancement can be mathematically quantified by what has become known as the Purcell factor F [82], defined

as:

$$F = \frac{3}{4\pi^2} \frac{\lambda}{n} \times \frac{Q}{V} \quad (2.38)$$

where λ is the wavelength of the emitted photon, Q and V are the quality factor and mode volume respectively, and n is the refractive index of the surrounding medium. The Q corresponds to the temporal confinement while the mode volume V represents the spatial confinement. Although cavity based structures can provide very high $Q(\sim 10^4)$ [83], they are consequently narrow bandwidth devices. This spectral limitation is a problem for contemporary solid-state quantum emitters which, despite many efforts in research, still have a broad spectral emission due to stability issues [84].

Optical nanoantennas, on the other hand have a much lower $Q(\sim 100)$ [85] and hence are suitable for applications involving broadband sources. However, due to surface plasmon polaritons, they have the capability to highly confine the light source volume well beyond the diffraction limit [86, 87]. Coupling optical nanoantennas with quantum structures like quantum dots can result in highly directive quantum emitter intensity pattern, but with a mode volume as low as $.002 (\lambda/n)^3$ [85] which corresponds to a very high Purcell factor of $\sim 5 \times 10^4$.

2.6.6 Aperture Antennas

So far in this chapter on-surface optical antennas have been emphasized primarily because there is considerable current scientific and industrial interest in the design of antennas for optical and near infrared communications. However, there is also significant industrial interest in antennas that are effective in focusing light to sub-wavelength dimensions. A primary application lies in the possibility of extending current photolithographic techniques to produce circuit chips on a sub-wavelength scale using relatively inexpensive optical equipment as compared to ion-beam etching machines. Nano-aperture antennas have been the key component in sub-wavelength

lithographic research and also been a key element in the development of several other technologies that will be discussed in the *Applications* section. Below a brief treatment of the theory of optical aperture antennas is presented followed by an overview of selected designs that have received popular attention in the literature.

2.6.7 Optical aperture antenna theory

Although important nano-level aperture optics was carried out in the study of fluorescence molecules in the 1980's [88], the report by [89] of dramatically enhanced transmission through sub-wavelength holes in metal films, was an event that spurred widespread interest in optical aperture antennas. Because this phenomena, now known as extraordinary optical transmission (EOT), seemed to fly in the face of the widely accepted classical electromagnetic analysis by [90] and [91], there has been considerable scientific interest in the subject reaching to the core of surface plasmon theory. According to the classical theory, the power transmitted through an aperture in an infinitely thin metallic screen scales as the inverse fourth power of the aperture size in terms of wavelengths. If the screen is made to be of finite thickness, then an additional reduction in the transmitted field strength will result, due the below-cutoff dimensions of the slot. However, it was discovered, first experimentally and then confirmed by numerical analysis, as shown in Fig. 2.13, that for metals at optical frequencies there are situations where remarkable

amounts of energy pass through sub-wavelength slits and holes. Fig. 2.13 illustrates a cross-sectional view of a metallic sheet made of silver with two slots passing through the sheet. This nanostructure is excited by a plane wave from below. The magnitude of the field intensity shows a complicated structure with significant field at the slot corners, an interaction resulting in strong standing waves in the horizontal direction below, some weak field transmission through the slots, and a standing

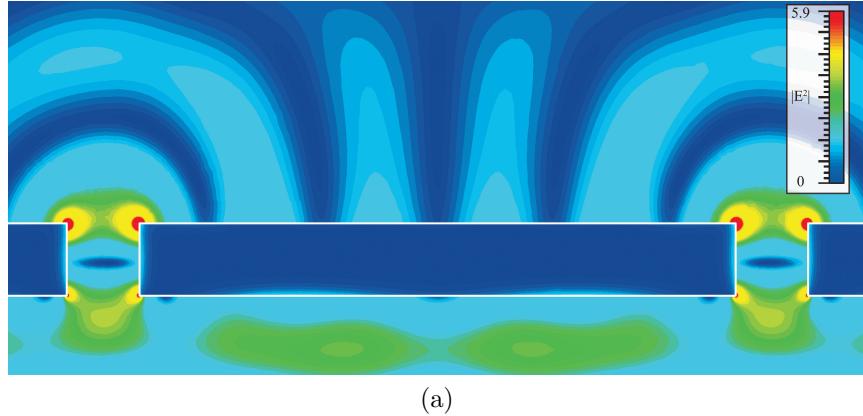


Figure 2.13: Simulation showing a surface plasmon standing wave intensity ($|E|^2$) pattern on a thin silver plate with dielectric constant $\epsilon = -18.242 + j1.195$ between two slots illuminated by a 660 nm plane wave from below. The center plate has a length $5/2\lambda_{spp}$ (1650 nm) and each aperture has a width and thickness of 200 nm.

wave pattern on top of the center plate. Although [89] explained EOT in terms of surface plasmon polaritons, others [92, 93] questioned the existence of surface plasmons and asserted that the observed phenomena could be explained by the existence of evanescent waves arising in a classical electromagnetics analysis not used by Bethe and Bouwkamp. However, a more detailed study that evolved through a series of technical papers confirmed the original EOT hypothesis [94, 43]. In the following, a purely mathematical analysis is presented revealing the nature of transmission through sub-wavelength holes including the surface plasmon, a space wave in the vicinity of the aperture, and a lateral wave behavior on the metal surface at distances over 100 surface plasmon wavelengths removed from the aperture. The importance of this analysis lies in the fact that surface plasmon radiation plays a more significant role in optical aperture radiation than does diffraction. Also because many applications require optical apertures with narrowly focused beams, it is important to know that significant energy is carried in surface plasmon polaritons on the surface of the metal on the side opposite the aperture excitation.

A thin slot aperture is modeled by placing a 2-D magnetic line current on the air-metal interface along the y-axis, into to the page, as shown in Fig. 2.2. This arrangement gives rise to a transverse magnetic (TM) field, which has three non-zero electromagnetic field components H_y , E_x and E_z . A straightforward analysis yields the magnetic field along the air-metal boundary:

$$H_y(x) = -\frac{k_0}{2\pi\eta_0} \int_{-\infty}^{\infty} \tilde{G}(k_x) e^{-jk_xx} dk_x \quad (2.39)$$

$$\tilde{G}(k_x) = \frac{1}{\tilde{D}(k_x)}, \quad \tilde{D}(k_x) = \frac{k_{z2}}{\varepsilon_2} + \frac{k_{z1}}{\varepsilon_1}, \quad k_{zi} = \sqrt{k_i^2 - k_x^2}, \quad \text{for } i = 1, 2 \quad (2.40)$$

where $\tilde{G}(k_x)$ is the Green function in terms of the spectral variable k_x , ε_1 is the dielectric constant of the upper half-space and ε_2 , containing a negative real part, is the dielectric constant of the metal lower half-space. Assuming the permeabilities of the two regions are the same as that of free-space, the location of the surface wave pole k_{xp} , which can be found analytically by setting $\tilde{D}(k_x)$ to zero, is $k_{xp} = k_0 \sqrt{\varepsilon_1 \varepsilon_2 / (\varepsilon_1 + \varepsilon_2)}$ as predicted by (2.6). The corresponding residue is:

$$R_p = \frac{1}{\tilde{D}'(k_{xp})}, \quad \tilde{D}'(k_x) = -k_x \left(\frac{1}{\varepsilon_2 k_{z2}} + \frac{1}{\varepsilon_1 k_{z1}} \right). \quad (2.41)$$

The spectral domain Green function $\tilde{G}(k_x)$ has branch points at k_1 and k_2 , respectively the wavenumbers of air and the metal at optical frequencies. Air is lossless, so k_1 is real and therefore lies on the real axis, as shown in Fig. 2.14, whereas metal has significant loss, so k_2 is far removed from and below the real axis. The field can be obtained by integrating in the k_x -plane along the real axis, path C_0 , from minus to plus infinity by means of the definitions $\text{Im}(k_{z1}) < 0$ and $\text{Im}(k_{z2}) < 0$ on the top sheet of the complex plane for both branch cuts. Integration on the real axis can be

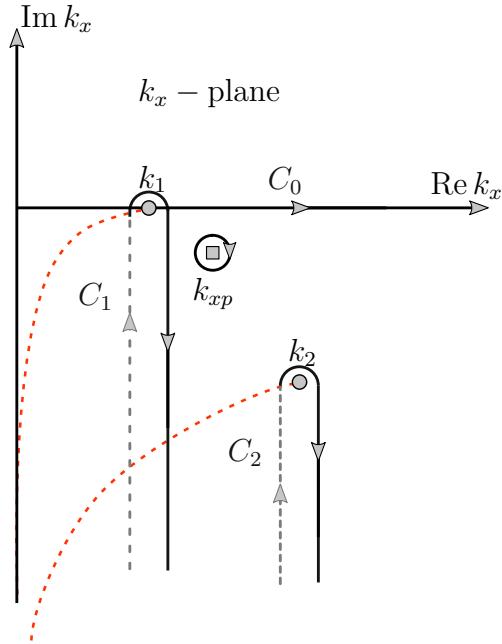


Figure 2.14: Complex plane integration path around branch cuts connecting the branch points k_1 and k_2 , the wavenumbers for air and metal respectively, and the SPP pole k_{xp} .

improved upon by deforming the integration path vertically so that C_0 is replaced by C_1 and C_2 , paths of steepest descent in the k_x -plane. An important consequence of the optical properties of a noble metal is that the position of the pole k_{xp} is such that it is captured by the vertical path deformation. Had the real part of the dielectric constant of metal been positive, the pole would reside to the left of the integration path below k_1 and therefore, it would not be captured by the integration path. It has been shown that poles captured by the steepest descent path are physical waves, in this case a surface plasmon wave, whereas poles not captured are not actual waves although they do influence the behavior of the field through their proximity to the integration path [95]. The contribution from the integral C_2 around the branch point at k_2 is negligible because the branch point lies well below the real axis so exponential decay due to the imaginary part of k_x is significant. The spatial domain Green

function can now be expressed in terms of its pole and branch point components as,

$$G(x) = \underbrace{\int_{C_1} \tilde{G}(k_x) e^{-jk_x x} dk_x}_{\text{Composite Wave}} + \underbrace{\int_{C_2} \tilde{G}(k_x) e^{-jk_x x} dk_x}_{\text{Negligible}} - \underbrace{2\pi j R_p e^{-jk_{xp} x}}_{\text{SPP Wave}}. \quad (2.42)$$

A careful analytical study of the composite wave shows that subtracting the surface plasmon polariton pole from the C_1 integrand yields a negligible result. However, when the pole is added back the resulting analytical expression yields the following limiting case forms [43],

$$I_p(x) \sim \begin{cases} x^{-1/2}, & \text{for small and moderate distance } x \\ x^{-3/2}, & \text{for sufficiently large distance } x \end{cases} \quad (2.43)$$

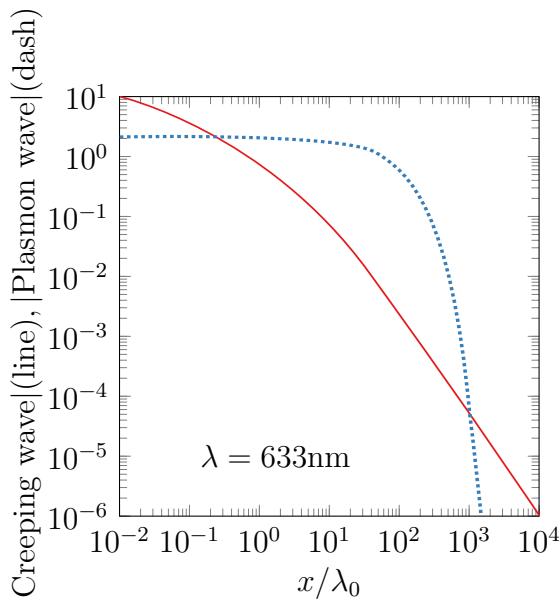
At small or moderate distances from the aperture (magnetic line source) the magnetic field has a $x^{-1/2}$ behavior, the same as the small argument behavior of a Hankel function for a line source in free-space, is often referred to as the ‘space wave’. At large distances, the $x^{-3/2}$ decay is typical of a lateral wave behavior.

Numerical results displaying the composite wave (solid line) and surface plasmon polariton wave (dashed line) where the metal is silver and the line source is radiating at 633 nm and 2500 nm are shown in Fig. 2.15 below. As predicted the dominant behavior of the magnetic field near the aperture is the $x^{-1/2}$ space wave. However at greater distances the plasmon wave becomes dominant, and in Fig. 2.15a close to 500 wavelengths where the plasmon wave tends to rapidly decay, the lateral wave behavior $x^{-3/2}$ dominates. Fig. 2.15b shows that at 2500 nm, the surface wave amplitude is reduced due to losses that enter the numerical calculation through the dielectric function given in Fig. 2.5. Eventually, at frequencies below the near

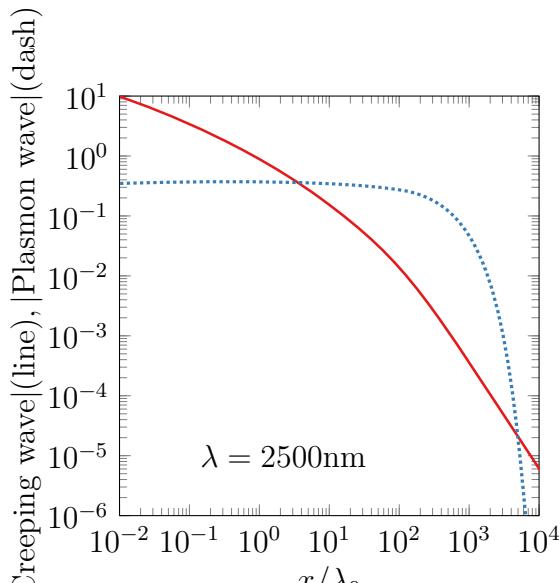
infrared range, the metal begins to behave more like a perfect conductor and the space wave completely dominates the behavior of the field. This exercise confirms the existence of the plasmon wave and displays its relationship to other wave phenomena produced in the aperture of a sub-wavelength slot and on the air-metal interface. More important from an antenna engineering standpoint is that energy carried by the plasmon wave through the slot does radiate into the space wave above the slot. The question, “Can a plasmon wave pass through a slot?” is answered by the analysis at the beginning of this chapter and in an excellent review covering analytical methods used to determine the properties of subwavelength apertures [96]. Because a surface plasmon wave is tightly bound to the metal surface, decaying to $1/e$ at distances far less than a wavelength above the metal walls, its expression in a waveguide is not governed by the typical waveguide boundary conditions. Plasmon waves in the two walls of the slot, although not entirely independent of one another, are not subjected to cutoff conditions, and can therefore carry much more energy than a waveguide evanescent mode or even an infinite sum of evanescent modes. The conclusion that can be drawn from this analysis is that at optical wavelengths, a significant amount of plasmon energy can be transported through a metallic slot with a sub-wavelength width. Because the slot is sub-wavelength in width, it is possible to form an array of plasmonic radiators to focus an intense beam to a sub-wavelength line or spot.

2.6.8 Bowtie aperture antenna

Many aperture antennas are a simple Babinet equivalent of their metal counterpart. The aperture bowtie, also known as the diabolo antenna, is one such design. The aperture bowtie shown in Fig. 2.1c differs from the well-known metal bowtie nanoantenna in that the opposing pair of aperture triangles are connected through an aperture extension of the facing triangular tips. Thus instead of a large charge



(a)



(b)

Figure 2.15: Logarithmic scale comparison of composite wave and surface plasmon polariton wave normalized amplitude for an air-silver interface as a function of distance from the source at (a) 633 nm (b) 2500 nm

density accumulating between the triangles across the air gap, a high optical current density develops within the gap but between the narrowly spaced metal sides of the gap. A high intensity enhanced field component is achieved in the gap connecting the apposal triangular arms by polarizing the incident light parallel to the narrow gap connecting the arms. Polarizing the incident field across the narrow dimension of the gap will produce little or no field enhancement. One of the interesting properties of the aperture bowtie is that the magnetic field rather than the electric field is enhanced in the gap. By analogy, the metal bowtie behaves more like an electric dipole and the aperture bowtie more like a magnetic dipole. Numerical simulations have shown a 2900-fold enhancement of the magnetic field at a wavelength of 2540 nm, confined to a $40 \times 40\text{nm}^2$ region near the center of the nanoantenna.

Although in general aperture antenna enhancement is not as high as can be achieved with a similar metallic structure, apertures are easier to make and have the advantage of providing a visual objective. The aperture bowtie has been shown to have sufficient enhancement and confinement to be effective in nanolithography applications [97]. The effectiveness of the aperture bowtie nanoantenna in nanolithographic applications is attributed to the fact that the magnetic field created in the aperture gap above the photoresist mask enters the mask in the perpendicular direction, easily penetrating into the metal, thereby leading to noticeable dissipation effects [98].

Optical tweezers are instruments that use light to move microscopic particles. Most often this requires a high powered focused laser beam to provide the necessary force to trap and move the particle. Optical tweezers are often needed in biological applications and are expected to have important applications in the construction of nano-machines. A variant on the bowtie design has been shown to create an optical vortex in the electromagnetic field [99]. The unusual field pattern is such that a small

particle moving away from the center of the vortex experiences increasingly higher forces pointing back towards the center. The aperture bowtie provides the user the ability to see the particle while manipulations are carried out.

2.6.9 Concentric Rings

Perhaps the most useful aperture antenna enhancement design is a concentric ring structure. In cross-section the ring has the appearance of a shallow trough etched into the metallic surface. Concentric rings have been incorporated around a variety of aperture designs with the goal of concentrating the transmitted signal into a narrow beam or to gain maximized reception. A single radiating aperture must be large in terms of wavelengths and contain a flat planar phase front in order to concentrate the signal. A common example at microwave frequencies is a parabolic dish antenna which in practice will have an aperture size of at least 10 wavelengths. However, a typical single sub-wavelength aperture antenna will have a large beamwidth. In order to provide directionality, an optical aperture antenna can be modified by adding the concentric ring structure which in essence provides a Bragg reflection condition for plasmon current waves traveling out from center. Another way of looking at the concentric ring design is that it provides an external impedance match condition for the source driven aperture.

Again, because metal at optical frequencies has a behavior similar to that of a dielectric, at least in terms of boundary conditions, numerical solutions provide the only route to design criteria for concentric rings. The number of grooves, groove width, groove depth, periodicity of the grating, hole diameter, and the distance between the first groove and the driven aperture all play a role and are strongly interlinked in the design. However, a basic optimization criteria for bull's eye structures has been formulated based on extensive numerical studies. What follows is repeated from an

excellent discussion on the subject, which can be found in more detail in a paper by [100]: “The first item to define is the desired resonance wavelength which in turn determines the period of the structure. The choice of the hole diameter will then be determined by whether one would like optimal efficiency as normalized to hole area or highest absolute transmission. For the former, the diameter should be about half the period, but for the latter the aperture size can be increased. It should be noted that as the hole size increases relative to the period, the spectrum will eventually broaden which is a trade-off. The groove width should also be around half the period with a depth to width ratio at 0.4. The number of grooves should be just enough to reach saturation, typically around 6 to 10 grooves depending on the geometrical parameters.”

2.6.10 Arrays

Many other specialized aperture designs have been reported in the literature, although design information is scarce. Usually the designer can refer to the current microwave antenna literature as a starting point for a numerical parameter investigation to determine that proper dimensions for an optical antenna design. External to the antenna the array factor and standard microwave array methods will typically be applicable to optical antenna array design, assuming the aperture field information is known. That is, a computer code must be used to determine the near field and a suitable array factor can be applied to the aperture near field information to find the far field. The array elements can be square or circular or any one of the antennas discussed above. Rectangular shaped apertures are of particular interest since they are the Babinet equivalent of a dipole antenna. The half-wavelength resonance condition applies to the slot antenna of high conductivity and a half-wave slot leads to a resonantly enhanced and aperture confined electric field [51].

2.7 Applications of Optical Antenna

2.7.1 SNOM

Scanning near-field optical microscopy (SNOM), an important technique for visualizing biological systems, involves obtaining high resolution topographic and optical images with a cone shaped probe that scales down to the nano level at the tip. The need for high spatial, temporal and resolving power with subwavelength resolution was the driving factor in a move to the fiber aperture probe, essentially a tapered optical fiber with a nanoscale tip. Evanescent or non-propagating fields that exist only near the surface of the object carry the high frequency spatial information about the object and have intensities that drop off exponentially with distance from the object. Because of this, the detector must be placed very close to the sample in the near field zone, typically a few nanometers. However, the aperture probe suffers from diffraction of light at the tip, which reduces its imaging resolution. Present research is centered on finding an antenna design that reduces the fiber beamwidth, thereby improving resolution. Although fabrication of tips true to the design criteria and surface smoothness are significant challenges to be overcome, a number of antenna structures such as the bowtie, Yagi and several plasmonic nanosphere probes have been tried out showing successful improvement in many cases.

2.7.2 Photon emitters and optical fluorescence

Single photon emission from a quantum emitter generates a stream of photons. Single photons can be used in a number of technologies such as Computed Tomography (CT), which is an imaging technique able to provide 3D information. A single quantum emitter positioned inside the subwavelength size feed gap of an optical antenna couples to the antenna, radiating in such a way as to be considered to be an impedance matching device. The density of the emitted photons thereby increases,

improving the tomographic image.

Solid state light-emitting devices are expected to eventually replace fluorescent tubes as illumination sources. Quantum dot nanocrystals are very promising for light-emitting sources. However, their light-emission efficiencies are still substantially lower than those of fluorescent tubes. It has been observed that quantum emitters in close proximity to a plasmonic producing metal surface causes plasmonic fluctuations of the free electron gas. The associated currents radiate, in many cases with a significant increase in intensity. Antenna structures such as the bowtie have been designed, optimized in size, shape, and material properties to increase the radiation efficiency of a nanoscopic optical source. However, for visual appeal, sources with greater optical bandwidth are needed [44, 101].

2.7.3 Raman Spectroscopy

Molecules vibrate, rotate and translate in a number of ways when exposed to an electromagnetic field. Raman spectroscopy is an optical technique used to detect the vibrational modes. It relies upon detection of a very low intensity portion of the scattered wave spectrum called inelastic or Raman scattering. Because molecules of a particular type, such as anthrax or mold aflatoxins, have a certain Raman spectra they can be identified by this method. However, because the Raman spectra is very small, very intense laser light is required in order to move the Raman signal above the noise level. Plasmonic nanoantennas create highly enhanced local fields when pumped resonantly, leading to increased Raman scattering [102].

2.7.4 Communication with nanocircuitry

As circuit chips become smaller and processer speeds increase, wire leads to the circuitry become less practical and less efficient. However, nanoantennas can overcome these drawbacks, with more efficient and on chip created optical antennas

communicating over wireless links to external circuitry. Cross-talk and the many problems with computer interconnects can be eliminated. One of the properties of on-surface optical antennas is that most of the radiated energy travels downward into the chip substrate. This can become an advantage where the construction of a via through the nano chip is impractical. A proper nanoantenna design would allow the circuitry to rapidly communicate back and forth directly through the substrate.

2.8 Conclusion

In this chapter, an overview of the field of optical antennas has been presented along with some of the basic theory of plasmonics, the underpinning concept governing electromagnetic wave behavior at optical frequencies. It was shown that surface plasmon polaritons lead to a set of requirements and restrictions placed on the design of antennas constructed out of noble metals at optical and near infrared frequencies. An unusual aspect of plasmonic waves in metals is their subwavelength behavior, an advantage when detecting small particles but it can cause added difficulty when impedance matching an optical antenna to free-space. It was shown that the surface plasmons explain the unusual amount of radiation coupled through a subwavelength aperture and that as a consequence aperture optical antennas are remarkably efficient, behaving in a manner similar to their Babinet equivalent counterpart. Spectroscopy, disease and toxin sensors, wireless communication with nano circuitry and the creation of nano circuits using sub wavelength lithography are some of the early beneficiaries of this new technology. The field of nano plasmonics offers great opportunities for optical frequency circuit and antenna engineers with the future easily as bright as it is for the modern day wireless engineer.

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