# Slow-light transmission in the metal-dielectric structure based on plasmon-induced transparency

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## ABSTRACT

The slow light technology prompts the realization of the all-optical storage, by which one can store the information of different wavelengths at their corresponding locations. The induction of plasmon induced transparency (PIT) provides a reliable and easy implement way to achieve slow light transmission and optical storage on the nanometer scale. Meanwhile, the linewidth and position of the PIT can be adjusted by changing the parameters of materials and structures, rather than just depend on the atom level itself in Electromagnetically induced transparency (EIT). More importantly, it can also be integrated with semiconductor devices on the chip, which is an exciting expectation for optoelectronic integration. PIT technology can pave a new way to optical information processing.

**Keywords:** Plasmonics; Slow light; Electromagnetically induced transparency (EIT)

## 1. INTRODUCTION

In recent years, a growing number of researchers are working on the metal-dielectric-metal (MDM) structures (including parallel, ring and three-dimension structures). Some potential applications of the MDM structures have been validated through theoretical calculation and simulation, including the beam splitters, optical switches, interferometers, couplers and filters [1, 2]. Electromagnetically induced transparency (EIT) can be generated by different methods, including quantum coherence effects in the dispersion medium of gas, solid, photonic crystal and silicon waveguide [3, 4]. The above method can slow down the speed of light in varying degrees (a few meters per second or less with different corresponding bandwidths) [5, 6]. EIT-like can occur in plasmonics to get slow light, even optical storage can be achieved in this way, refers to the studies in recent years [7-10]. Here, we call this technology as plasmon induced transparent (PIT). It can overcome the diffraction limit in the micron or even nano-devices. Furthermore, the line width, dispersion and group velocity of the PIT wave can be changed by altering the structure parameters. Using "transparent" and "plasmonics" as the keywords in the Google Scholar search, we can find the number of papers about PIT is growing each year over the past decade. Fig. 1 shows that the number may turn out to nearly two thousand in 2013.

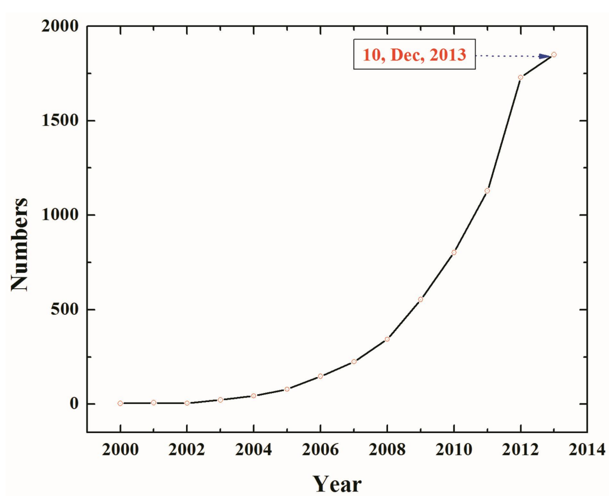


Figure 1. The number of papers about PIT over the past decade.

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The PIT plasmonic devices can be achieved in the metal structure with different materials, different patterns and complex multi-dimensional structures.

## 2. METAL-DIELECTRIC-METAL STRUCTURE

The PIT phenomenon in the two-dimensional grating plasmonics can be explained by the characteristic impedance model and transmission line theory. Take the MDM grating structure for example, as shown in Figure 2. The structure is composited by a metal wall and a metal grating with a period of $d$ and depth of $L$. The width of the internal medium is $b$ and the width of the air-waveguide is a .

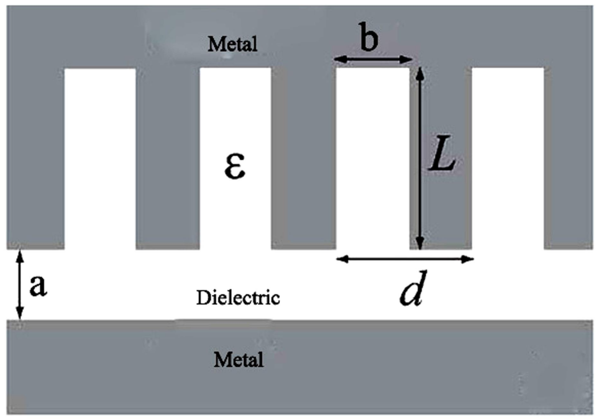


Figure 2. The schematic structure of MDM.

In this structure, the disperation relation between the angle frequency $\omega$ and the Bloch wave vector $\gamma = \alpha + i\beta$ of the grating MDM system is shown as[11]

$$\cosh(\gamma d) = \cosh^2\left(\gamma_0 \frac{d}{2}\right) + \sinh^2\left(\gamma_0 \frac{d}{2}\right) + \frac{Z_1}{Z_0}\sinh\left(\gamma_0 \frac{d}{2}\right)\cosh\left(\gamma_0 \frac{d}{2}\right)\tanh(\gamma_1 L) \tag{1}$$

Where, $\gamma(\gamma_{0,1})$ is the complex wave vector of the TM mode in MDM; $Z_0 = \gamma_0 a / i\omega\varepsilon$ is the impedance of direct waveguide; $Z_1 = \gamma_1 b / (i\omega\varepsilon)$ is the impendance of grating and $\omega = 2\pi c / d$ is the angle frequency of grating. When $\omega \to 0$, one can got the corresponding slowdown factor from Equation 1, which can be expressed as

$$\frac{c}{v_g} = \sqrt{1 + \frac{\omega L}{\omega_0 d}} \tag{2}$$

Where, $c$ is the light velocity in vacuum, $v_g$ is the group velocity of MDM structure, $\omega_0$ is the angle frequency of the incident light.

## 3. SIMULATION RESULTS

From the above equation, one can modulate the slowing factor by changing the geometrical parameters of the structure, e.g., reducing the width of the dielectric layer will result in the increasing of slow down factor. The nano-structures can be typically prepared by the electron beam lithography and UV or other chemical etching methods. Figure 3 shows the MDM waveguide with rectangular and triangular tooth structures.

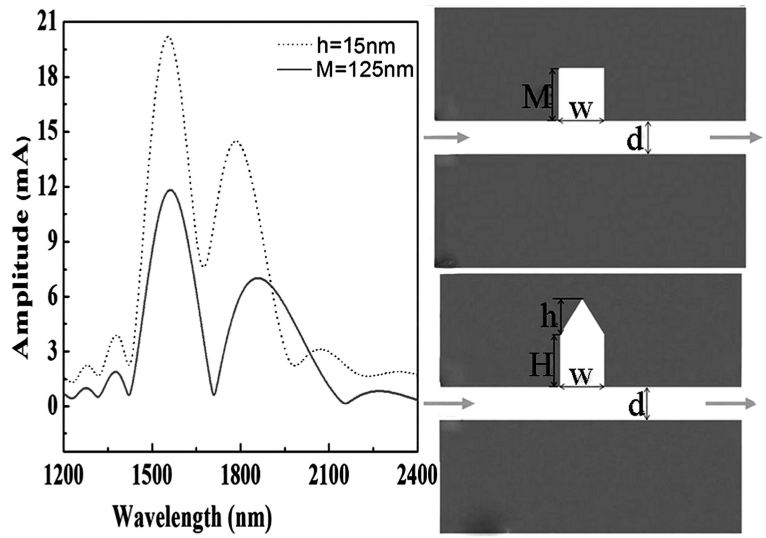


Figure 3. The transmitted power spectrum of the different MDM waveguides at 1550nm.

When the tooth structure is added in the waveguide, we get two separate transmission peaks in the power spectrum, as shown in Figure 3. The relationship between the light-field and the micro-structural parameters is discussed in both the rectangle-tooth and triangle-tooth waveguides. The width of the direct waveguide d = 50nm, tooth structure width w = 50nm. The rectangle structure has a depth of M. The height of the rectangle and triangle in the triangle-tooth waveguide is H and h, respectively. Figure 3 indicates the power spectrums in the two structures [rectangle-tooth waveguide (the solid line) and triangle-tooth waveguide (the dot line)] with the same tooth depth, that is M = H + h = 125nm (H = 110nm, h = 15nm). It is clear that the impact on the light field derives from the two structures has the significant differences.

To explore the impacts of the microstructure parameters on the light field, we calculated the power spectrums for different structures by changing the parameters of the tooth in MDM waveguide (such as M, h). In the simulation, we gradually change the depth of the rectangular and triangular toothed structure, and calculate the transmission spectrum of the MDM nano-structures with different geometric parameters. The results show that, by changing the tooth depth (the depth of triangular teeth h gradually increase from 10nm to 70nm; the depth of rectangular teeth M gradually increase from 85nm to 125nm), the decreases of the transmitted light intensity can be clearly observed at the two peaks overlap (about 1700nm) in the power spectrum of transmitted light. When the depth of triangular teeth h=70nm, and the rectangular teeth M=125nm, the overlap rate of two peaks is 0, the light at this wavelength is completely cut-off, as shown in Figure 4.

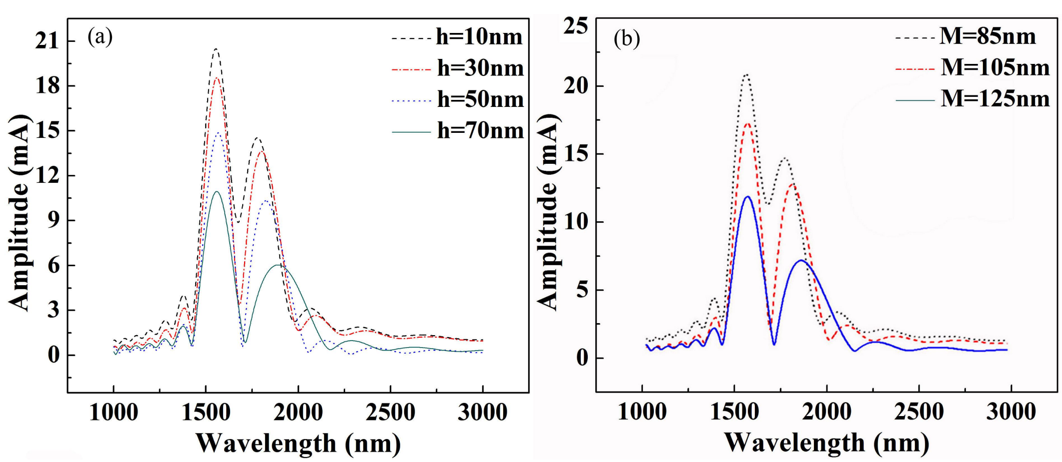


Figure 4. Transmitted power spectra of triangle (a) and rectangle (b) structure for different tooth depth.

Meanwhile, in the triangular teeth structure, the depth of the triangle tooth h is gradually increased from 10nm 70nm, while the peak amplitudes of both left and right peaks are decreasing, the right peak shifted to right, and the two sub-peaks at the sides of main peak is gradually suppressed. Rectangular tooth structure shows the similar results. The transmittance between the two peaks decreases gradually with the tooth depth's increasing, which is located in the middle and re-rises up as an EIT-like peak with the further increasing of M (or h), as shown in Figure 5.

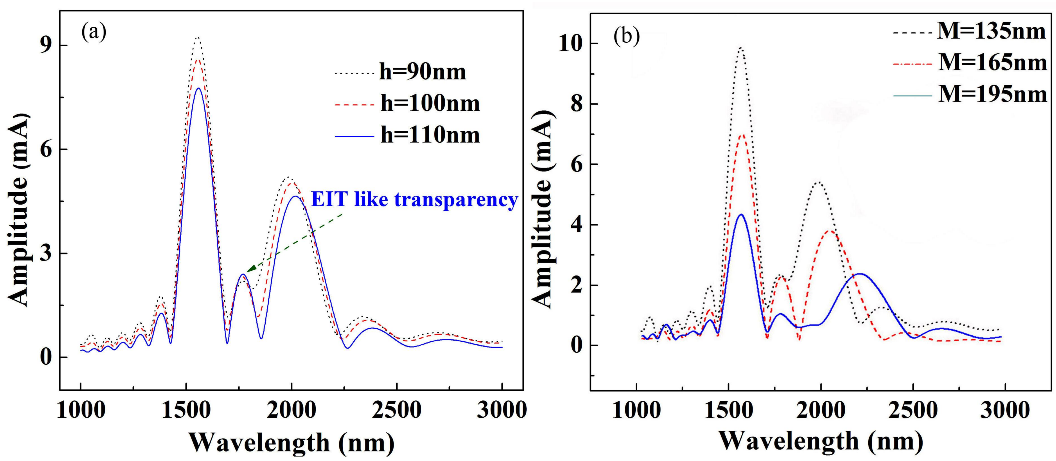


Figure 5. Transmitted power spectra of triangle (a) and rectangle (b) structure for different tooth depth.

It can be seen that, the positions and amplitudes of the left and center peaks can maintain, and the position of right peak will be modulated by increasing the tooth depth in the triangular tooth MDM nano-structure; the similar situation is exiting in the rectangular tooth structure. But the too large tooth depth will lead to the right and center transmission peaks weaken or even disappear, as shown in Figure 5(b). However, it can be observed in Figure 5(b) that the middle-peak can not increase continuously. In the rectangle-MIM-waveguide, the middle-peak begins to decay and all of the three transmission peaks decrease at the same time (here, M = 135nm). Simultaneously, the transmission peak on the right side keeps shifting to the long-wave range.

## 4. RESULTS ANALYSIS AND DISCUSSION

The distance between the left-peak and right-peak and their corresponding amplitudes are calculated, as indicated in Figure 6. The analysis in the triangle-tooth waveguide is given in Figure 6(a). Here, the red (dot) represents the left-peak amplitude; black (squares) represents the right-peak amplitude; blue (triangle points) represents the amplitude difference of the two peaks; green (open circles) represents the spacing between the two peaks. Figure 6(b) indicates the analysis in the rectangle-tooth waveguide, which is same to the Figure 6(a).

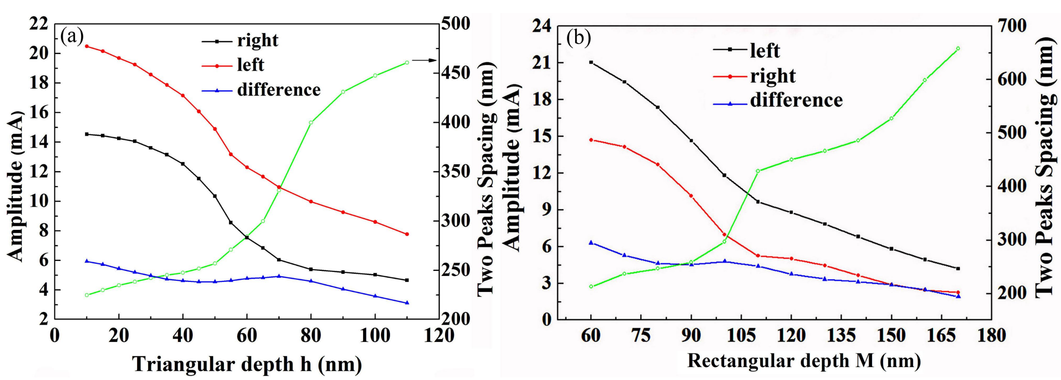


Figure 6. Two peaks' parameters vs tooth depth in two structures

In the analysis of the transmission characteristics of the MDM waveguide with triangle and rectangle nano-toothed structure, the rectangular toothed structure is found more suitable to achieve coarse adjustment of the transmission power spectrum in the wide range; the triangular tooth structure is applicable in the field of light fine adjustment. Bimodal peak difference in the rectangular tooth structure changes more obvious. In contrast, the power spectrum can be changed by means of the transmission to achieve the nano-structures detection, while this structure can also be used for light-field modulation near 1550nm.

## 5. CONCLUSION

In conclusion, we studied the impacts on the light field, owing to the tooth structures (such as triangle-tooth waveguide and rectangle-tooth waveguide) in the MDM waveguide. In the simulation, we calculated the power spectrum of the output light using different tooth parameters. By comparing the spectrums, we can conclude that the rectangle-tooth waveguide suits for coarse-adjusting the outgoing-light field in a wide range, since the two peaks amplitude and spacing are changing obviously in this structure. In contrast, the triangle-tooth structure is more suitable for the fine-tuning the light field. The two peaks amplitude difference of the triangle-tooth waveguide is greater than the rectangle-tooth waveguide, which indicates that the response of the peaks difference is more sensitive for the triangle-tooth waveguide. Therefore, it is reasonable to postulate that we can detect the tooth structure appearance of the MDM waveguide by observing the transformation of the output power spectrums. The results of this paper will be applied to light modulation, and nano-structure detection.

EIT has the good transparency and high damage threshold, but hard to control. The linewidth of EIT depends on the lifetime of the atomic resonance level based on quantum coherence. But for PIT, it depends on the dielectric constant of materials and the structure parameters of the plasmonic devices. The induction of PIT provides a reliable and easy implement way to achieve slow light transmission and optical storage on the nanometer scale. At the same time, the linewidth and position of the PIT can be adjusted by changing the parameters of materials and structures, rather than just depend on the atom level itself. More importantly, the plasmon nanostructures can also be integrated with semiconductor devices on the chip, which is exciting expectations for optoelectronic integration. PIT can rekindle the passion of researchers to develop a new road in optical information processing.

## ACKNOWLEDGEMENT

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