Guiding light in fluids

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In contrast to conventional waveguides with high-refractive-index core, we describe a concept for guiding light within a low-refractive-index medium surrounded by a medium with higher refractive index. This concept is especially compatible with fluidic sensors because the channel itself can be used as the core of the waveguide and thereby enabling a strong light-analyte interaction over an extended distance. The concept is based on antiresonant modes, and experiments have shown that these modes can be excited by collimating excitation light under an appropriate angle onto the waveguide structure. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2195075]

Applying optical methods to characterize biological and chemical analytes such as absorption, fluorescence, and Raman spectroscopy has gained lots of interest in recent years. One of the remaining challenges is the efficient delivery of photons to and from the analytes. Analytes are often in liquid and are moving along channels. It is favorable to have a large interaction length between light and analyte without losing or spreading light intensity. Waveguides have a high potential in these applications as they enable large volume interaction without creating a large amount of stray light. Of course, it is desirable to guide the light inside the fluid in order to achieve a maximum interaction of light and analyte. However, the fluid usually has a lower refractive index than the surrounding walls such that regular waveguiding mechanism cannot be applied to this problem. Many spectroscopic systems are therefore using the fluid as the cladding layer of a waveguide such that only the evanescent field of the waveguide mode is available for sensing.[1] This technique is restricted to analytes close to the interface and is not favorable to measure in large volumes.

Several approaches have been used to overcome these problems. Liquid core waveguides have been developed based on a Teflon cladding layer which has a lower refractive index than water.[2,3] Also, photonic crystals and fibers have been used to guide light in either medium including air and fluids.[4] Photonic crystals and hollow fibers are usually difficult and expensive to fabricate. Antiresonant reflecting optical waveguides (ARROWs) use interference reflection coatings which confine the light to the fluidic channel.[5,6] ARROWs have the disadvantage that the layered stack of interference coatings is optimized for a certain wavelength region only.

We have developed a new approach to effectively guide light in a liquid, low-refractive-index medium which avoids many of the above disadvantages. As will be shown later our concept is based on an antiresonant guided optical wave (ARGOW) in a layered structure shown in Fig. 1. A thin liquid layer with low refractive index is sandwiched between two glass slides which are surrounded by air. Light propagation in such a structure is similar to concepts published as "leaky waveguides" in the literature;[7] however, our waveguides are not leaky and therefore are not restricted to short waveguide lengths.

Understanding light propagation in waveguides is commonly done by looking at the optical modes in these structures. From this, the intensity distribution over the cross section of the waveguide is obtained and the confinement factor of the light within a certain layer of the structure can be determined. Calculating the optical modes results in a number of conventional and ARGOW modes, the latter revealing very high light confinement in the liquid compared to the conventional modes (e.g., up to 90%). The antiresonant modes can be excited by coupling light under a certain angle into the structure. For simplicity, this is explained in the following with the ray picture of light.

Figure 1 shows light entering the structure through the entry facet and its propagation at different coupling angles. For angles below a critical angle γ_c'' light is guided in the upper glass slide by total internal reflection (TIR) as in a conventional waveguide. No light is coupled into antiresonant waveguide modes and no light is guided within the water. γ_c'' is determined by Snell's law as follows:

$$\gamma_c'' = \arcsin\left[\frac{n'}{n''}\arccos\left(\frac{n}{n'}\right)\right]. \tag{1}$$

At the critical angle light at the glass/liquid interface is no longer blocked by TIR and ARGOW modes in the liquid are excited. Note that the critical angle is independent of the layer thickness.

The light is nearly parallel to the channel if the coupling angle is close to the critical angle. From this case we obtain the largest interaction because the ray propagates a long distance through the water layer before it couples into the opposite glass slide and later on back into the water. The stretch inside the water gets shorter for increasing coupling angle. The ratio between the horizontal distance which the beam travels through the water and it travels through the whole stack from A to B [see Fig. 1(b)] can be interpreted as the confinement factor:

$$\Gamma = \frac{d_W}{d_W + d_G}. \tag{2}$$

The confinement factor as a function of the coupling angle is shown in Fig. 2.

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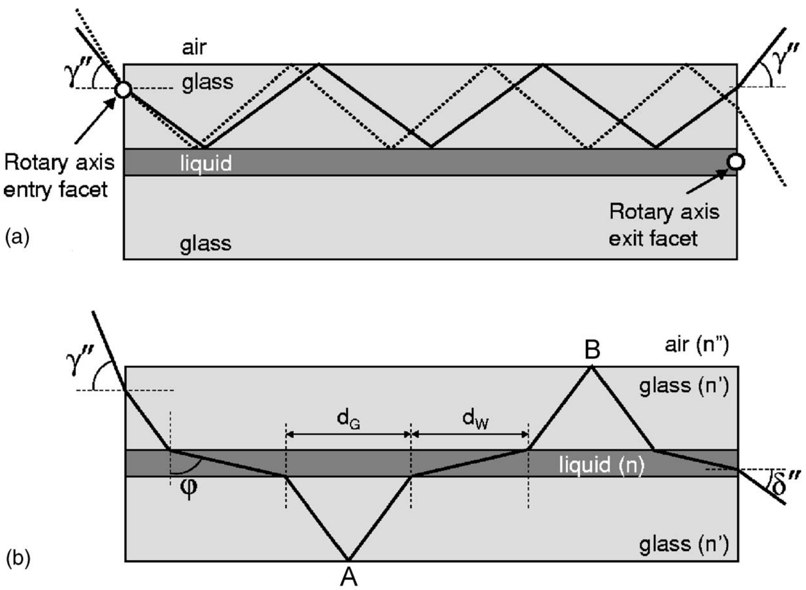

FIG. 1. Schematic illustration of light rays propagating through the waveguide structure at different coupling angles (a) below and (b) above the critical angle. (a) also indicates the position of the rotary axis of measurement setup. (b) From the path length of light in water and glass the confinement factor can be calculated.

For the experiments we used a 160 μm thick, 2 mm wide, and 50 mm long water film sandwiched between two 1 mm thick microscope glass slides spaced apart by microscope cover slides. The refractive indices are $n=1.33$ (water), $n'=1.51$ (glass), and $n''=1$ (air); this results in a critical angle of 45° [Eq. (1)]. Our measurement setup consists of a well collimated 632 nm He–Ne laser with a beam cross section that is smaller than the 1 mm thick facet of the glass slides. The laser is mounted on a rotary stage with the rotary axis positioned exactly at the front facet of one of the glass slides as indicated in Fig. 1. At 0° the laser beam is exactly parallel to the waveguide stack. At the opposite side a second rotary stage with the rotary axis positioned, as shown in Fig. 1, at the end facet of the liquid channel holds a Si photodiode with a variable aperture in front of it. Both rotary stages can be controlled with a precision of 0.1°.

In a first experiment the photodiode is fixed at 0° and a microscope objective collects the light emitted out of the end facet of the waveguide. The aperture is regulated such that the photodiode is exposed only to light emanating from the water film between the glass slides. Figure 2 shows the light intensity at varying coupling angle. The light intensity in the water film is low as long as the coupling angle is below 45° and increases by nearly three orders of magnitude once the critical angle is passed. Figure 2 also compares these measurements with the theoretical confinement factors obtained from Eq. (2).

The integral between 45° and 52° of the measured data was normalized to the integral of the theoretical curve in the same angular spectrum. The "noisy" behavior above 45° is due to interference effects of the highly coherent laser light; the interference pattern is highly sensitive to the coupling angle and therefore the measured intensity varies by a factor of 2 or more if the coupling angle is changed by the smallest increment of our measurement setup of 0.1°. To study the interference pattern in more detail a smaller increment of the coupling angle is required. Overall the intensity is decreasing as the coupling angle is increased as predicted by the theoretical curve. Although the theoretical model for the confinement factor neglects the ray splitting which occurs at the glass/water interface it reveals the experimental findings as displayed in Fig. 2.

Also, the sharp onset is comparable for the measured and calculated curve. Before the sharp onset of the intensity the measured intensity increases by one order of magnitude. This is caused by scattering of the laser light at the imperfection at the polished entry facet (see the square symbol in Fig. 3). A fraction of light inside the glass already propagates under an angle above the critical angle and therefore enters the liquid as indicated by a diamond in Fig. 3.

The oscillatory behavior at coupling angles smaller than 40° can by interpreted by looking at Fig. 1(a). In this angular range light is purely guided within the coupling glass slide

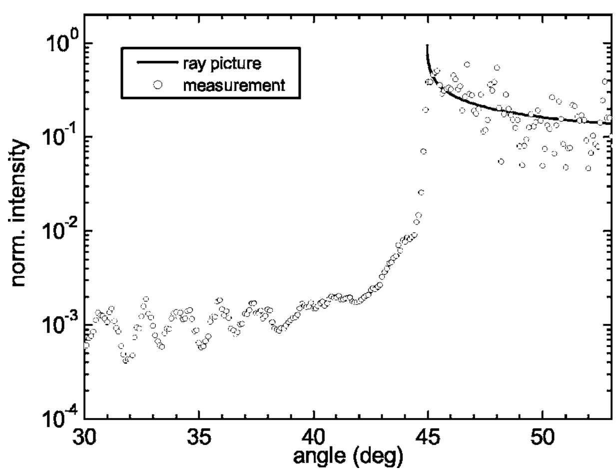

FIG. 2. Light intensity in water film at the end facet of waveguide at varying coupling angle and comparison with predictions from the ray model of light.

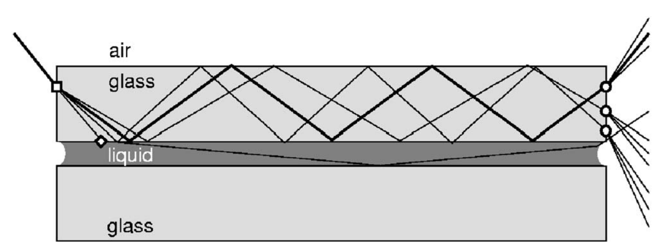

FIG. 3. Schematic illustration of light scattering at entry and exit facets of waveguide.

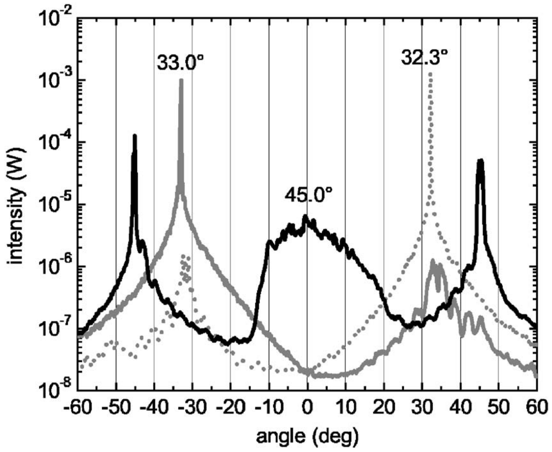

FIG. 4. Intensity profile at the waveguide end facet at different coupling angles. Below the critical angle (32.3° and 33.0°) the light distribution is asymmetric, whereas it is symmetric above the critical angle (45.0°).

and it depends on the coupling angle and the length of the waveguide in which direction the light leaves the glass slide. In the experiment we observed that the maximum intensity occurs right at the coupling angle where the beam is changing direction at the end facet. Due to light scattering at the edge of the glass slide the detector receives more stray light at these special angles and detects it as light coming out of the water layer.

In a second experiment we kept the laser fixed at different angles and detected the output intensity at the end facet of the waveguide over an angular range from −60° to +60° using a rather small aperture of 0.3 mm in front of the detector in order to achieve a high angular resolution. Results are shown in Fig. 4 for two coupling angles below the critical angle (32.3° and 33.0°) and one just above the critical angle of 45.0°. Below the critical angle the angular distribution is highly asymmetric with respect to a mirror plane at 0°. Depending on the coupling angle the light beam is exiting the end facet either upwards after an odd number of reflections or downwards after an even number of reflections [Fig. 1(a)]. Therefore, we are detecting a high intensity either on the right (positive) side of the distribution (e.g., at a coupling angle of 32.3°) or on the left (negative) side of the distribution (e.g., at 33.0°). In each case the dominant peak is surrounded by a background signal at both sides of the distribution which occurs due to light scattering at the exit surfaces indicated by the circles in Fig. 3. This background signal shows oscillations because light beams will still go either up—or downwards if they are scattered at the entry facet as indicated by a square in Fig. 3.

It is clearly visible that the intensity distribution is changing above the critical angle. It is now symmetric with respect to the mirror plane at 0° and it has two sharp peaks which occur at the same angles at the left and right sides of the distribution and a broad distribution symmetrically around 0° (Fig. 4). In the antiresonant waveguiding scheme light can reach the end facet either in one of the two glass slides or the water layer. If the light is coupling out of the glass slides it will do it under the same angle as is it was coupled in. Therefore, the sharp peaks at −45° and +45° are due to light which emanates out of both glass slides either up—or downwards as discussed before. The center peak, however, is due to light which leaves the end facet through the water channel. The light is propagating in the water under a well defined angle, and therefore the distribution should show two sharp peaks on the left and right sides of the distribution at an angle in accordance with Fig. 1(b) and

$$\sin \delta'' = \frac{n}{n''} \cos \varphi. \tag{3}$$

However, the end facet of the water layer is not as straight as the glass facet, but is instead curved inwards due to capillary forces as depicted in Fig. 3. This curved water surface is acting as a concave lens spreading the light into a broad angular distribution.

The area underneath each peak gives experimental evidence for the amount of light that is guided inside the liquid. Integrating the intensity distribution over the whole angular range results in a total light intensity of 18.8 μW. This is the total amount of light which is guided through the waveguide. The integral over the light intensity that emanates out of the water layer from −20° to +20° is 8.2 μW. This results in a confinement factor of 44%, meaning that 44% of its path the light is guided inside the liquid whereas during the rest it is located in the glass. For sensing applications one should keep in mind that light which leaves the waveguide at the end facet through the glass slide has been interacting with the water as well. As can be seen in Fig. 1(b) light is partly propagating in the glass and partly in the water while it is propagating through the structure.

We have demonstrated a new technique to efficiently guide light within a liquid film using an antiresonant waveguide concept consisting of a liquid film sandwiched between two glass slides. Exciting antiresonant guided optical waves turned out to be very efficient when the excitation beam is directed under an appropriate angle onto the facet of one of the glass slides. Snell's law determines the coupling angle where the total internal reflection at the glass/liquid interface ceases. Experiments prove that the light intensity interacting with the liquid is increasing drastically as soon as the critical angle is passed. The confinement factor was determined experimentally by detecting the light intensity distribution at the end facet of the waveguide. The experimental findings are in very good agreement with the theoretical values.

These findings are very valuable for biosensing applications, especially for absorption or fluorescence spectroscopy. The concept enables large interaction lengths between the target analytes and the excitation light by using a very simple structure. Fluorescence light can be easily detected in this configuration as the structure is transparent and the reemitted light can leave the structure through the top or bottom glass layer, whereas the excitation light is guided.

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