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Low loss surface electromagnetic waves on a metal–dielectric waveguide working at short wavelength and aqueous environment

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ABSTRACT

A metal–dielectric waveguide (MDW) structure was presented to generate surface electromagnetic waves (SEWs) suitable for short wavelength (<500 nm) working in aqueous environment. Aluminum thin film was employed to adapt for the short wavelength and silica layer was introduced to form the low loss surface mode, whose energy is mainly confined at silica/water interface. Transfer matrix theory was used to investigate theoretically the above ideas, and the process to design and optimize the structural parameters of the MDW structure for the SEWs was also introduced. Experiments were performed to validate the existence and the low loss nature of the SEWs, and the wavelength of the excited SEW was measurement by a home-built near field scanning system which accords well with the theoretical prediction. This type of SEWs on a MDW structure can be as an alternative to overcome the limitations associated with the traditional metal-type waveguide mode such as surface plasmon polariton, and could be potential for applications like the imaging, bio-sensing, precision measurement, etc.

1. Introduction

Surface wave exists in many forms in nature. In mechanical form, a typical example is an ocean surface wave [1], while a ground wave is a well-known example of an electromagnetic form, which refers to the radio-frequency waves propagate parallel and adjacent to the surface of the earth [2,3]. If the wavelength decreases to the optical frequency region, it becomes an evanescent wave that exists whenever a total internal reflection occurs [4]. This evanescent wave has a form of traveling wave along the interface while decays rapidly in the perpendicular direction. An intriguing application associated with evanescent wave is the total internal reflection fluorescence microscopy (TIRFM) [5–9], which enables super-resolved imaging with high signal-to-noise ratio owing to the exponential decaying of the electromagnetic field intensity out of focus.

As an exceptional form of evanescent wave, surface plasmon polariton (SPP), an eigen surface electromagnetic wave (SEW) supported at the interface between metal and dielectric, drew great attention in the past two decades [10]. The SPP arises when light interacts with free electrons in the metal under a certain condition (wave-vector matching condition), causing the free electrons oscillating collectively and resonantly with the incident radiation [11]. The resonant and evanescent nature of SPPs makes them suitable for a variety of applications including ultra-high sensitive bio-sensing [12,13], surface-enhanced Raman spectroscopy [14], structured illumination microscopy [15–19], miniaturized and integrated optoelectronic devices [20,21], etc.

Although the SPP-based techniques bear many advantages, this kind of metal waveguide, nevertheless, suffers an intrinsic large Ohmic loss, particularly at a short wavelength near the ultra-violet region. This impairs greatly the performance of the aforementioned plasmonic techniques, and even causes them invalid. For instance, gold and silver SPP waveguides exhibit a good performance at the long wavelength region in the visible spectral range; however, they present a bad response or even become inactive at the short wavelength region, e.g., the blue light region. While the aluminum waveguide shows a relatively good response to the blue light, the mode loss is yet not small enough for a practical application. Particularly when it comes to an aqueous condition (for most of the bio-applications), the situation becomes even worse. This remarkable shortcoming may cause either large measurement errors or small field-of-view in bio-sensing and imaging applications.

Here, we present a metal–dielectric waveguide (MDW) that is suitable for short wavelength and aqueous environment. Aluminum is employed as the metal material because it remains active at the blue light or even shorter wavelength region.

By lying one more loss-free dielectric layer above the metal-film [22–24], a kind of MDW mode is supported at the structure, with a SEW formed at the dielectric–water interface. As compared to an SPP mode, the MDW mode shifts most of the energy from metal surface to the dielectric–water interface, which lowers significantly the loss of the mode. In this paper, transfer matrix theory was applied to illustrate the design of the MDW structure and experiments were carried out to

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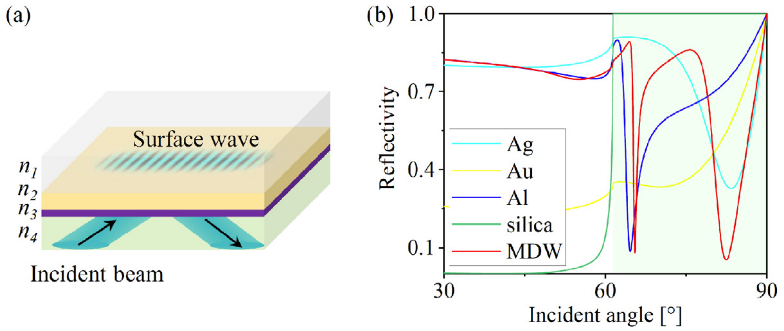

Fig. 1. (a) Schematic of the proposed MDW structure which from top to bottom, are the water environment (n_1 = 1.33), silica layer (n_2 = 1.46), thin aluminum film (n_3 = 0.684 + 6i @473 nm) and glass substrate (n_4 = 1.515), respectively. (b) The comparison of reflection curves of different configurations, including the Ag-SPP waveguide, Au-SPP waveguide, Al-SPP waveguide, the silica-only waveguide and the MDW, respectively. All of the structures are in the aqueous environment. The region for total internal reflection is marked by a green background. The excitation wavelength is 473 nm in (b) and the parameters are as follows: Ag and Au film thickness — 45 nm, aluminum film thickness — 20 nm, silica layer thickness — 500 nm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

validate the theoretical predication. A home-built near-field scanning imaging system is employed in the experiment to verify the existence of the designed-SEW and to measure the wavelength of the excited-SEW. The proposed MDW operates well at short wavelength and in water environment, which is expected to have a great application potential in bio-sensing and bio-imaging.

2. Theoretical model

The metal–dielectric waveguide structure that supports the SEWs is shown in Fig. 1, which is a four-layer system composing of a thin film of metal (thickness d_3) sandwiched between a dielectric layer (thickness d_2) and glass substrate, with water as a superstrata. According to the transfer matrix theory, the reflection coefficients of a multilayer system can be evaluated by [4]:

$$r = \frac{\left(m_{11} + m_{12}p_1\right) p_4 - \left(m_{21} + m_{22}p_1\right)}{\left(m_{11} + m_{12}p_1\right) p_4 + \left(m_{21} + m_{22}p_1\right)} \tag{1}$$

$$t = \frac{2p_1}{\left(m_{11} + m_{12}p_1\right) p_4 + \left(m_{21} + m_{22}p_1\right)} \tag{2}$$

where p_i= cosθ_i/n_i, (i = 1, 2, 3, 4), θ_i is the emission angle of the ray in each layer with respect to the normal direction, which is governed by the Snell's law, n_i the refractive index of each layer. The matrix elements (m_{11}, m_{12}, m_{21}, m_{22}) are determined by the characteristic matrix as:

$$M = M_3 M_2 = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \tag{3}$$

$$M_i = \begin{bmatrix} \cos\beta_i & -\frac{i}{p_i}\sin\beta_i \\ -ip_i\sin\beta_i & \cos\beta_i \end{bmatrix}, i = 2, 3 \tag{4}$$

where $\beta_i = k_0 n_i d_i \cos\theta_i$, with k_0 represents the incident wave vector in the free space. Finally, the reflectivity can be obtained by $R = |r|^2$.

At a shorter wavelength in the visible spectral region, for example, 473 nm as demonstrated in this paper, the SPP metal-waveguide bears a rather high Ohmic loss, particularly in an aqueous environment as shown in Fig. 1(b), where a series of reflection curves are calculated for various configurations. The wide and shallow dip associated with the reflection curve of Ag-SPP-waveguide (cyan color) illustrates a rather high-loss SPP mode, and the curve for an Au-waveguide reveals even the absence of resonance (yellow color) because the inter-band transition of electrons becomes dominant which makes the dielectric constant of Au not be suitable to support an SPP mode [11]. While the metal waveguide with a 20 nm-thickness aluminum film shows an SPP mode with a relatively lower loss to those of the above (blue color), it is still not good enough from the practical point of view, particularly when the working wavelength is further decreased to the near ultraviolet region. Instead, by depositing a silica layer (500 nm-thickness for the calculation) onto the 20 nm-thickness aluminum film to form a MDW, a much lower loss mode is formed at an incident angle of 65.47° as illustrated with the red curve in Fig. 1(b). For the purpose of comparison, we also calculated the reflectivity curve when the aluminum layer in the MDW is removed (green color), which is pretty like a response of a total internal reflection configuration without any resonance. It indicates that both a thin metal film and a silica layer are necessary in order to generate this kind of low loss surface mode.

To optimize the MDW structure to achieve a better performance, both the thickness of the Al thin film and the silica layer are considered. We first fix the thickness of silica layer to 500 nm while varying the thickness of Al-film to study the metal-layer effect on the resonance. The calculated result is illustrated in Fig. 2(a) where the thickness of Al-film is set at the range of 0–60 nm. The reflectivity contour map shows a sharp and deep dip when the thickness of Al film is ~20 nm, demonstrating that the MDW supports a SEW with rather low loss under this circumstance. Subsequently, the Al-film is set at a thickness of 20 nm while we vary the thickness of silica layer to study the dielectric-layer effect, with the calculated result shown in Fig. 2(b). It can be seen that the resonance angle (and accordingly the wavelength) of the surface mode, which refers to the upper sharp bright line, is changed. This provides us a convenient way to tune the wavelength of the SEWs in a certain range by simply adjusting the thickness of the dielectric layer. For instance, the thickness of silica layer should be set at 560 nm if one would expect to excite an SEW with 340 nm wavelength, as demonstrated in the experiment in the text below. It should be noted that the wide bright regions lie on the right-side in Fig. 2(a–b) correspond to the SPP mode supported at the Al-silica interface, illustrating the high loss nature of the mode.

3. Experimental results

Experiments were performed to verify the above predictions. The schematic of setup is shown in Fig. 3(a). A laser beam with 473-nm-wavelength was used as light source. After passing through a linear polarizer, a telescope and a half-wave plate, the collimated beam with linear polarization is reflected by a mirror and is tightly focused onto the MDW structure by an oil-immersion objective (150 ×, NA = 1.45, Olympus), to excite the SEW at the dielectric layer surface. The MDW structure is with an aluminum film with 20 nm-thickness and a silica layer with thickness of 560 nm, and is embedded in an aqueous environment. The reflected beam after passing through a beam splitter and an optical lens is captured by a CCD (charge coupled device) camera at the back focal plane (BFP) of the objective. For the purpose of comparison, the reflected beams from a SPP waveguide with 20 nm-thick Al film and that from the above MDW structure are captured respectively by the CCD camera, with the images shown in Fig. 3(b) and