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Article in Journal of optics · December 2014
DOI: 10.1088/2040-8978/17/1/015003

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Dispersion analysis and engineering of 2D plasmonic waveguides

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Received 7 July 2014, revised 24 September 2014
Accepted for publication 13 October 2014
Published 17 December 2014

Abstract
A full investigation of the low-order guided modes in a two-dimensional (2D) hollow metallic waveguide is performed. The dispersion characteristics of the 2D hollow metallic waveguides are identified and analyzed. Manipulating the dispersion is proposed by either changing the geometrical shapes from rectangular to trapezoidal waveguide or changing the material of the cladding region to TiN. The dispersion analysis of the 2D plasmonic waveguide using TiN is investigated for the first time. The effect of varying the shape parameters on the cutoff in the modes dispersion is studied. The trapezoidal shape waveguide that causes the most significant shift in the cutoff is selected and detailed dispersion analysis of its guided modes is performed. The effect of changing the plasmonic material on the dispersion curve key characteristics is also identified. Finally, the effect of shifting the cutoff on the enhanced transmission phenomena is investigated.

Keywords: plasmonic, enhanced transmission, subwavelength optics, extraordinary transmission (EOT) phenomena

1. Introduction
Plasmonic waveguides offer the possibility for increased confinement of the propagating modes, promising a subwavelength photonic infrastructure suitable for integration on silicon-based photonic chips [1]. By providing the basis for subwavelength photonic devices, plasmonic waveguides could help reduce the size mismatch between electronic systems (currently being built on a scale as small as 22 nm) and typical photonic devices (usually built on the scale of the light wavelength or slightly smaller [43]). Hence, plasmonic waveguides play an important role in embedding photonic systems into nanoscale electronic systems. Although plasmonic waveguides suffer the drawback of increased losses, many applications are not blocked by such drawback because the nature of these applications lacks the need for a large propagation length. Examples of such applications include sensing applications and extraordinary transmission (EOT) phenomena [36–39]. Various types of plasmonic waveguide structures have been proposed, including metallic gap [2–4], wedge [5], groove [6], nanowires [7], and the metal–insulator–metal (MIM) plasmonic waveguide. MIM and insulator–metal–insulator (IMI) structures, in particular, have a range of interesting applications and have received attention from many researchers [8–19, 45]. There is great interest in MIM because of the relative simplicity of the manufacturing process for such waveguides, and the range of applications MIM can be used in (such as the negative refractive index and slow light [20–24], sensing and interconnecting applications—like using an MIM slot waveguide to guide light through a low-index region [25]—and in multiplexed sensing using a Mach–Zehnder interferometer [26]). In the work presented here, we investigate whether a rectangular waveguide can offer MIM applications for both polarizations. A detailed mathematical study for MIM and IMI waveguide-guided modes, including symmetric and
asymmetric cases where the upper and lower claddings have different refractive indices, is performed in [9]. The numerical analysis of Ag/SiO$_2$/Ag MIM waveguide-guided modes dispersion, with a focus on the long-range propagation and the high spatial confinement characteristics of the waveguide, is conducted in [25]. Little investigation has been conducted in the literature to identify the guided modes of the rectangular plasmonic waveguide with sufficient details and completeness. Most studies for this waveguide type have been limited to a certain effect or phenomenon at a specific wavelength band [27, 28]. We anticipate that a rectangular plasmonic waveguide can offer greater capabilities in comparison to MIM because, although all interesting applications of MIM waveguides exist for a single polarization, the rectangular metallic waveguide can offer such capabilities for both polarizations, as found in [29]. Swillam et al [29] discovered, through numerical analysis, the existence of a $x$- and $y$-polarized guided modes in the rectangular metallic waveguide and studied their dispersion characteristics and applications. Applications such as sensing and energy transmission have been identified for the rectangular plasmonic waveguide, which has shown a much higher sensitivity than the MIM waveguide [29].

Different regions of the dispersion curve for the modes identified in [29] can be exploited in different applications, such as sensing, enhanced transmission, slow and fast light, and the negative index of refraction applications. Based on that, there are two objectives for this paper. The first objective is to perform a more detailed modal analysis for the rectangular plasmonic waveguide by identifying all key guided modes and their dispersion relations. The second objective is to investigate how the dispersion curves for the key modes can be engineered and manipulated through shape and material variations, which can be helpful because different regions in the dispersion curves can be exploited in different applications, as mentioned previously. The shape variation process studied in this work is changing the shape from rectangular to one of possible trapezoidal plasmonic waveguide shapes. To our knowledge, this is the first work to study 2D trapezoidal plasmonic waveguides with dielectric filling. The study of the effect of varying the material on the key modes dispersion is accomplished by using TiN in comparison to silver.

In section 2, we briefly review the formulation for the MIM lowest-order guided modes, as well as the numerical analysis approach adopted in this work, which is based on full vectorial finite-element analysis and employed in a commercially available tool [30]. We then focus on performing a detailed analysis of the dispersion characteristics of a 2D plasmonic rectangular waveguide with dielectric filling. In section 3, we discuss the possible geometrical ways of manipulating the rectangular shape into a trapezoidal shape and its effect on the cutoff in the rectangular waveguide-guided modes is identified. Detailed dispersion analysis of the guided modes in the trapezoidal shape that causes maximum shift in cutoff is also performed. In section 4, the dispersion analysis of the 2D plasmonic waveguide using TiN is investigated for the first time. The effect of varying the cladding plasmonic material from silver to TiN on the dispersion of key guided modes is discussed. In section 5, an investigation of the effect of cutoff shift on enhanced transmission peaks is conducted. Finally, the conclusion is given in section 6.

2. Rectangular plasmonic waveguide key guided modes

2.1. MIM Waveguide key guided modes formulation

A rectangular plasmonic waveguide with dielectric filling can be viewed as the intersection between a horizontal MIM waveguide and a vertical MIM waveguide. For that reason, we present a brief review of the MIM waveguide-guided modes dispersion before performing a numerical modal analysis for the rectangular metallic waveguide because we expect that the guided modes in the rectangular plasmonic waveguide will be related to, or derived from, the guided modes in the MIM waveguides. A detailed formulation for MIM and IMI waveguide lowest-order modes has been given in [9, 31]. An important result from the MIM waveguide analysis in [31] is that when the upper and lower claddings are made from the same metal, the dispersion relation can be split into the following pair of equations:

\[
\tanh(k_d a) = \frac{-k_m \epsilon_d}{k_d \epsilon_m} \quad (1)
\]

\[
\tanh(k_d a) = \frac{-k_d \epsilon_m}{k_m \epsilon_d} \quad (2)
\]

In equations (1) and (2), the thickness of the dielectric layer is $2a$. Here, $k_d$ and $k_m$ are the components of the wave vector in the dielectric material and the metal material, respectively, perpendicular to the metal–dielectric interface. The reciprocals of $k_m$ and $k_d$ represent the decay lengths perpendicular to the interface in the metal and dielectric layers respectively. Here, $\epsilon_m$ and $\epsilon_d$ are the dielectric functions of the metal and dielectric layers, respectively. In the coordinate system shown in figure 1, based on the extensive study done by Prade et al [9] for MIM- and IMI-guided modes, $z$ is the
direction of propagation and equation (1) represents odd modes—that is, Ez is odd, whereas Hx and Ey are even. On the other hand, equation (2) represents modes with even parity—Ez is even, whereas Hx and Ey are odd. Hence, for the lowest-order modes in the MIM waveguide structure, it is expected to find both fundamental even and odd modes.

2.2. Numerical method and geometrical structure

In this paper, we conduct a numerical modal analysis of a 2D rectangular plasmonic waveguide structure using the finite-element method to solve a full vectorial wave equation. Finite-element analysis based on the full vectorial wave equation considers polarization coupling and allows for high index differences in the waveguide being simulated. The geometrical structure for the rectangular metallic waveguide is shown in figure 2. A typical size used throughout this paper, as well as in other research on the enhanced transmission phenomena in rectangular holes [28, 32], is for the dielectric filling to have a width of 270 nm and a height of 105 nm. The boundary conditions employed are periodic boundary conditions. The boundary conditions are chosen to be periodic to facilitate a study of the EOT phenomena [37, 38] through an array of holes near the cutoff wavelength discussed later. The distance from the dielectric center to the adjacent dielectric center in a hole array is 450 and 300 nm in the x- and y-directions, respectively.

2.3. Rectangular plasmonic waveguide key guided modes

An investigation has been conducted for the guided modes in a rectangular plasmonic waveguide with the geometry shown in figure 2 and the dimension of 270 × 105 nm, where the metallic region is chosen to be silver and the dielectric is air. Palik’s experimental values for the permittivity of silver have been used [33]. Because of the numerical modal analysis using Comsol [30], four low-order key guided modes have been identified and shown in figure 3. The four guided modes seem to resemble the odd and even mode components’ parity of the vertical and horizontal boundaries of the dielectric rectangular region if both act as MIM waveguides. The discovered modes are referred to as combinations of vertical (V), horizontal (H), even (E), and odd (O). By investigating the mode profile of the discovered modes, we find that the vertical odd (VO) mode in figures 3(a)–(c) has a low-order odd Ez component and low-order even Ex and Hy components, which matches what would be expected from the profile of the odd mode in a vertical MIM waveguide (parallel to the y-axis) [9, 31]. In addition, the vertical even (VE) mode profile in figures 3(d)–(f) matches the expected profile for an even mode of a vertical MIM, as it has even Ez and odd Ex and Hy components. Similarly, the horizontal odd (HO) and horizontal even (HE) mode profiles shown in figures 3(g)–(l) match what would be expected for the key odd and even modes of the horizontal MIM waveguide (parallel to the x-axis) [9, 31]. This suggests that the rectangular plasmonic waveguide key guided modes might be related to, or derived from, the key guided modes of the two MIM waveguides formed from the vertical and horizontal boundaries of the rectangular waveguide. Hence, some of the benefits of the guided modes of two MIM waveguides of different sizes might be encapsulated in the guided modes of a single rectangular waveguide. It is worth mentioning that the HO- and VO-guided modes are similar, in terms of spatial mode profile, to the widely known TE10- and TM11-guided mode profiles, respectively, in rectangular metallic waveguides at microwave frequencies. However, there is a red shift in the cutoff wave-length of the HO mode compared to the TE10 microwavenguided mode. As indicated in figure 4, the cutoff wavelength of the HO mode is around 760 nm, whereas the cutoff wavelength for a TE10 microwave mode in a rectangular waveguide of 270 × 105 nm should be around 2*270 = 540 nm [44]. A detailed study of the red shift in the cutoff of the TE10 mode due to the plasmonic effect has been previously published [42]. Also, for the TM11 microwave mode, it is expected that the cutoff wavelength for a 270 × 105 nm rectangular waveguide will be around 195 nm [44]; however, the cutoff wavelength of the VO-guided mode is around 440 nm, as shown in figure 4, indicating a red shift as well. To identify possible applications for the rectangular plasmonic waveguide-guided modes, dispersion analysis is needed.

An investigation of the dispersion relation for the four key guided modes is shown in figure 4, where the effective index is plotted against the wavelength. The solid lines represent the real part of the effective index, whereas while the dashed lines represent the imaginary part. It is noticed that a rectangular waveguide of 270 × 105 nm offers a cutoff in the VO- and VE-guided modes at around 440 nm and another cutoff in the HO-guided mode at 760 nm. The dispersions of VO- and VE-guided modes for the vertical (short) boundaries are very similar. When comparing the HO and VO dispersion curves, we notice that the general shape of the curves is similar; however, the HO-guided mode has its cutoff red shifted to 760 nm, whereas the cutoff in VO curve is at 440 nm. This can be a possible indication that increasing the length of certain boundaries in the dielectric region boundaries causes a red shift to occur in the cutoff of their respective odd modes, because the length of the horizontal
boundaries causing HO is larger than that of the vertical boundaries causing VO. It is noticed also that the VO and HO curves have their dispersion peaks at approximately the same wavelength (around 350 nm). This indicates that, although increasing the length of any of the dielectric region boundaries (vertical or horizontal) causes red shift in the cutoff of its respective odd mode (VO or HO), this does not red shift the dispersion peak as well. By red shifting the cutoff while the peak still at the same position, a stretch of the region from the peak to the cutoff occurs. Hence, the slope of such region can be manipulated by adjusting the length of the dielectric region boundaries. Although the dispersion curves for VO and VE caused by the vertical (short) boundaries are almost identical, this is not the case for the dispersion curves of HO and HE caused by the horizontal (long) boundaries. The HE-guided mode of the rectangular waveguide has a negative effective index imaginary part. This can be explained because the wave in the HE mode is a backward wave [24]. It is also noticed that the HE-guided mode vanishes below 330 nm.

3. Dispersion engineering through shape variations: from rectangular to trapezoidal waveguide

In this section, we investigate how the dispersion curves for the rectangular waveguide-guided modes can be manipulated...
by varying the waveguide shape from rectangular to trapezoidal. There are several possible geometrical outcomes for shape variation from rectangular to trapezoidal. Figure 5 shows possible geometrical structures for a trapezoidal waveguide. Abbreviations have been created, as shown in figure 5, to uniquely identify different trapezoidal structures. An important parameter for the trapezoid structure shape is the side ratio $d$, which represents the ratio between the parallel sides (shorter side divided by longer side). For each possible trapezoidal waveguide shape, the HO and VO mode profiles for the $E_z$ component are shown in figure 5.

When the side ratio is 1, the trapezoid is rectangular, whereas at a side ratio of 0, the trapezoid is triangular. An investigation is conducted on the effect of changing the shape from a rectangle to a trapezoid on the cutoff wavelength found in the VO- and HO-guided modes. The study has been performed by changing a rectangular metallic waveguide to different trapezoidal structures with different side ratios $d$. In addition to the $270 \times 105$ nm dimensions, we also explored, in the variation study presented in this section, a $600 \times 360$ nm dimension with a center-to-center distance of $1200 \times 1000$ nm between adjacent holes in the hole array. The choice of these particular dimension sets is due to their popular use in EOT phenomena literature [29, 36–39]. EOT is an important application of the plasmonic metallic waveguide and is discussed in section 5. The results of both dimension sets show similar trends in the cutoff shift for various trapezoidal structures. Figure 6 shows the effect of varying the rectangular waveguide’s geometrical shape to a trapezoidal shape on the mode cutoff wavelength for the dimensions $600 \times 360$ nm. Only results for the $600 \times 360$ nm dimensions are shown, as the results for $270 \times 105$ dimensions show the same trends in cutoff changes but with smaller variation, due to having smaller dimensions for the dielectric region. However, the larger dielectric dimensions of $600 \times 360$ offer more significant changes in cutoff due to their larger footprint [42]; hence, these dimensions serve as a better demonstration for cutoff variations. The cutoff wavelength for the VO and HO modes of a rectangular waveguide of size $600 \times 360$ nm is 850 and 1370 nm, respectively. Figures 6(a) and (b) show the shift in cutoff wavelength over side ratio range from 0 to 1. Figure 6(c) shows the maximum cutoff shift achieved in each trapezoidal structure for VO- and HO-guided modes. The largest side ratio $d$ at which the maximum shift is achieved is shown at the end of each bar in figure 6(c). It can be noticed from figure 6(c) that, for the HO mode, the VTRL trapezoidal structure causes the maximum blue shift in the mode cutoff wavelength, whereas the HTL and HTR structures are the only structures that cause a red shift in the HO mode. For the VO mode, the VTRL structure is the only trapezoidal structure that causes a red shift in the VO mode cutoff wavelength, whereas the HTTB structure causes the maximum blue shift in the VO mode cutoff.

Table 1 shows the maximum propagation length in the various structures discussed so far. The rectangular plasmonic waveguide studied previously has its HO mode providing the largest propagation length of $2.67 \mu$m at a 600 nm wavelength. Modes HE and VE provide the lowest propagation length and suffer maximum losses among the four identified modes. For the trapezoidal structures with dimensions based on $270 \times 105$ nm, the maximum propagation length for the HO and VO modes are identified indicating that HO mode provides the largest propagation length at 670 nm for VTR and VTL and at 590 for HTR and HTL. In fact, the effective indices and maximum propagation lengths of the HO and VO modes are found to be identical in VTR and VTL as well as in HTR and HTL. This indicates that the modes are actually identical in each pair. HTTB and VTRL have their maximum propagation length in the HO mode at 580 and 550 nm, respectively. Based on table 1 data, the HTL, HTR, and HTTB structures are superior to VTL, VTR, and VTL in terms of propagation length of the HO mode and achieve closer values to the rectangular waveguide HO mode maximum propagation length. This indicates that the longer the horizontal borders of the dielectric region, the higher the maximum propagation length in trapezoidal structures represented in the HO mode.

Because the VTRL structure shows an interesting behavior among the other trapezoidal structures by causing the maximum blue shift in the HO mode cutoff and the only red shift in the VO mode cutoff, as shown in figure 6, dispersion analysis for the VO and HO modes in the VTRL structure at side ratio $d=0.3$ is conducted. Figure 7 shows the dispersion curves of the VO- and HO-guided modes for the VTRL trapezoidal structure. The VTRL structure is derived from a $270 \times 105$ silver rectangular waveguide with air filling and has a side ratio $d=0.3$. It is shown in figure 7(a) that the dispersion curve for the HO-guided mode in the trapezoidal VTRL structure has its cutoff blue shifted to 670 nm in comparison to the rectangular waveguide cutoff at 760 nm. The peak of the dispersion curve in both cases is approximately at the same position, which indicates that by exploiting the observed blue shift in the cutoff, we can increase the magnitude of the slope of the curve segment from the cutoff
Figure 5. Possible trapezoidal waveguide structures for side ratio $d$ of 0.3. Each structure has a unique abbreviation derived from its shape: vertical trapezoidal with right concave angle (VTR), vertical trapezoidal with left concave angle (VTL), vertical trapezoidal with right and left concave angles (VTRL), horizontal trapezoidal with right concave angle (HTR), horizontal trapezoidal with left concave angle (HTL), and horizontal trapezoidal with top and bottom concave angles (HTTB). A trapezoidal is labeled vertical or horizontal when its base is parallel to the $x$- or $y$-axis, respectively. For each trapezoidal waveguide shape, the HO and VO mode profiles for the $E_z$ component are shown. The HO and VO mode profiles shown are calculated at 650 and 320 nm wavelengths, respectively.
to the peak and hence, control the group velocity and group velocity dispersion. On the other hand, in the dispersion curve for the VO-guided mode shown figure 7(b), the cutoff seems to be approximately at the same wavelength in both the rectangular and the VTRL waveguide cases. However, the peak in the VTRL case is slightly blue shifted in comparison to the peak in the rectangular waveguide case, which can be exploited by decreasing the magnitude of the slope of the curve segment from the cutoff to the peak.

4. Dispersion engineering through material variations: silver versus TiN

In this section, an example is given on manipulating the dispersion curve by maintaining the same shape but changing the material. A material can be changed for the core (dielectric) and/or the cladding (metal). Changing the core or filling has been demonstrated previously in literature and it was found that it shifted the dispersion curve \[29\]. The focus in this section is on changing the metal cladding material while maintaining an air dielectric core. An analysis of the dispersion relation between the VO- and HO-guided modes is performed when changing the material to TiN instead of silver. TiN has been selected for this example because it has recently received attention in literature as a possible alternative plasmonic material to traditional plasmonic materials such as gold and silver. TiN has been demonstrated to show plasmonic behavior in the visible and near-infrared frequencies. TiN also demonstrates better performance in transformation optics and metamaterial devices than
conventional gold and silver plasmonic materials. An inherit advantage of TiN is that it is compatible with standard silicon manufacturing processes, unlike gold and silver [34]. Naik’s experimental values for the TiN material dielectric function are used [35]. Figure 8 shows the dispersion curves for the HO- and VO-guided modes in both TiN and silver 270 × 105 rectangular waveguides with air filling. From figure 8(a), the cutoff for the TiN dispersion curve of the VO mode is around 600 nm wavelength at an effective index around 0.5. This indicates a large red shift in the dispersion cutoff in comparison to the silver waveguide VO mode cutoff at around 440 nm wavelength. The dispersion peak in the TiN VO mode is also red shifted to 400 nm when compared to that of the silver VO dispersion peak around 350 nm. The peak height in the TiN VO mode is almost half that of the silver VO mode. Similarly, in figure 8(b), the TiN HO mode has the dispersion cutoff and peak red shifted, where the cutoff is around 1100 nm and the peak is around 600 nm. The peak in TiN HO is also lower than that of the silver HO dispersion peak. In addition, the cutoff in case of TiN happens at an effective index around 0.5 instead of 0, as in the case of silver waveguide.

The data and results in this section represent an example on shifting the dispersion curve key characteristics using material manipulation. By selecting the appropriate plasmonic material, the waveguide designer can tune the rectangular waveguide to exploit its applications at different frequency ranges.

### 5. Near cutoff enhanced transmission analysis in rectangular and trapezoidal waveguide

In this section, an analysis of the near cutoff enhanced transmission [27, 28, 32, 36–39] in rectangular and VTRL trapezoidal waveguides is presented. The objective is to investigate the effect of the blue shift reported in the VTRL HO mode cutoff on the enhanced transmission phenomena for the VTRL structure. A numerical simulation using an finite difference time domain (FDTD) photonic simulation package [40] has been chosen for the enhanced transmission analysis. The simulated structure consists of a silver wall (modeled using the Lorentz–Drude model), which has an air hole at its center, with dimensions 270 × 105 in the rectangular case and a side ratio $d=0.3$ in the trapezoidal case. The thickness of the silver wall is 300 nm. Periodic boundaries are used in the transverse plan, whereas anisotropic perfectly matched layer

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**Table 1. Maximum Propagation Length in Studied Structures.**

<table>
<thead>
<tr>
<th>Structure</th>
<th>Mode</th>
<th>$L_{\text{max}}$ (nm)</th>
<th>Wavelength at $L_{\text{max}}$ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectangular</td>
<td>HO</td>
<td>2676.7</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>VO</td>
<td>107</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>HE</td>
<td>53.116</td>
<td>330</td>
</tr>
<tr>
<td></td>
<td>VE</td>
<td>89.801</td>
<td>390</td>
</tr>
<tr>
<td>VTRL</td>
<td>HO</td>
<td>1150.7</td>
<td>550</td>
</tr>
<tr>
<td></td>
<td>VO</td>
<td>74.14</td>
<td>150</td>
</tr>
<tr>
<td>HTTB</td>
<td>HO</td>
<td>2086.4</td>
<td>580</td>
</tr>
<tr>
<td></td>
<td>VO</td>
<td>64.472</td>
<td>320</td>
</tr>
<tr>
<td>VTR</td>
<td>HO</td>
<td>1293.8</td>
<td>670</td>
</tr>
<tr>
<td></td>
<td>VO</td>
<td>69.792</td>
<td>150</td>
</tr>
<tr>
<td>VTL</td>
<td>HO</td>
<td>1293.8</td>
<td>670</td>
</tr>
<tr>
<td></td>
<td>VO</td>
<td>69.792</td>
<td>150</td>
</tr>
<tr>
<td>HTR</td>
<td>HO</td>
<td>2154.7</td>
<td>590</td>
</tr>
<tr>
<td></td>
<td>VO</td>
<td>59.535</td>
<td>150</td>
</tr>
<tr>
<td>HTL</td>
<td>HO</td>
<td>2154.7</td>
<td>590</td>
</tr>
<tr>
<td></td>
<td>VO</td>
<td>59.531</td>
<td>150</td>
</tr>
</tbody>
</table>

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**Figure 7.** The dispersion curves of the VO- and HO-guided modes for the VTRL trapezoidal waveguide compared to respective modes in the rectangular waveguide. The VTRL structure is derived from a 270 × 105 silver rectangular waveguide with air filling and has a side ratio $d=0.3$. It is shown in figure (a) that the dispersion curve for the HO-guided mode in the trapezoidal VTRL structure has its cutoff blue shifted to 670 nm in comparison to the rectangular waveguide cutoff at 760 nm. The peak of the dispersion curve in both cases is approximately at the same position. For the VO-guided mode shown in figure(b), the cutoff wavelength is approximately at the same position in both the VTRL and the rectangular waveguide, yet the peak seems to be blue shifted in the VTRL waveguide case in comparison to the peak in the rectangular waveguide case. The inset images at the bottom left corners of figures (a) and (b) are for the mode profiles of the Ez component in the VTRL HO and VO modes, respectively.
(PML) boundaries are used as the z-plan boundaries. The source is a y-polarized Gaussian modulated continuous wave with wavelength 700 nm. Figure 9 shows the power spectrum normalized to the input power and the area for the rectangular air hole (solid line) and the trapezoidal VTRL air hole (dashed line). As seen from figure 9, the enhanced transmission peak in VTRL is blue shifted in correspondence to the cutoff blue shift reported in the previous section for the VTRL trapezoidal waveguide HO mode. The enhanced transmission curve also shows the well-known Rayleigh minima of Wood’s anomaly [41], reported previously in a similar enhanced transmission calculation by Ebbesen [37].

6. Conclusion

In this paper, a modal analysis of the key low-order guided modes in a 2D rectangular plasmonic waveguide has been conducted that reveals the existence of four low-order guided modes: VO odd mode, VE even–odd, HO odd mode, and HE even mode. The VO odd mode and VE even mode are related to MIM waveguide modes formed by the dielectric region vertical boundaries. Similarly, the HO and HE modes are related to an MIM waveguide modes formed by the horizontal boundaries. Dispersion analysis of the four guided modes of the rectangular plasmonic waveguide shows that each of the HO mode and the VO mode dispersions has a cutoff wavelength. The cutoff of the HO mode occurs at a wavelength larger than that of the cutoff wavelength of the VO mode due to longer horizontal boundaries, compared to the vertical boundaries of the dielectric region in the rectangular waveguide studied in this work. This implies that the cutoff location can be controlled by controlling the boundary lengths and that, by using rectangular plasmonic waveguide, we would gain the benefits of two wavelength cutoffs at different wavelengths proportional to the dielectric boundary lengths. A cutoff in the dispersion can be exploited in applications such as filtering and near cutoff EOT phenomena [38]. Such phenomena provide an interesting capability of transporting the electromagnetic energy with minimum losses by tunneling [36–39]. Engineering the structure to shift the cutoff to exploit its related applications in a desired wavelength range is investigated. Engineering the dispersion by varying the waveguide shape, from rectangular to different trapezoidal structures, is performed. Several possible geometrical outcomes for shape variation from rectangular to trapezoidal are identified and the variation effect on the cutoff wavelength in the VO and HO modes is investigated for all. The VTRL trapezoidal structure with side ratio $d=0.3$ is identified as the structure that causes the maximum blue shift in the HO mode cutoff. The maximum propagation length in rectangular and trapezoidal structures’ HO and VO modes is identified, which reveals that the HO mode has superior propagation length over other key modes. It also indicates that the larger the length of the horizontal dielectric boundaries, the greater the propagation length of the mode. Detailed dispersion analysis for the HO- and VO-guided modes of the VTRL structure with side ratio $d=0.3$ is then performed. It is found that, although there is blue shift in the cutoff of the HO mode, the peak in the mode dispersion (point of maximum effective index) is approximately at the same location, which means that the shift in the cutoff can be exploited to increase the magnitude of the slope of the dispersion curve segment from the peak to the cutoff. Increasing the slope can cause negative group velocity, which can be used in creating negative index metamaterials. In the VO mode, dispersion of the VTRL structure the cutoff is at the same position. However, the peak is blue shifted, which can be exploited by decreasing the magnitude of the slope of the dispersion curve segment from the peak to the cutoff. By decreasing the magnitude of the dispersion slope, the waveguide in this region can be exploited in band pass applications where small variations in the effective index are desired over a range of wavelengths. This implies that the VTRL HO mode can be used not only to blue shift the cutoff, but also to increase the slope of the dispersion curve and cause negative
group velocity. On the other hand, the VTRL VO mode can be exploited to decrease the slope of the dispersion for band pass applications. We investigated the effect of using TiN instead of silver as a plasmonic material for the cladding. A red shift was identified in the dispersion cutoff and peak for the VO and HO modes in TiN rectangular waveguide compared to their counterparts when using silver. This demonstrates an additional approach for shifting and engineering the dispersion by varying the dielectric material rather than the shape of the waveguide. Finally, we investigated the near cutoff EOT phenomena in the VTRL structure in comparison to the rectangular structure. It was found that the EOT peak is blue shifted in correspondence to the blue shift in the VTRL structure cutoff.

Acknowledgment

This research was partially funded by Zewail City of Science and Technology, American University in Cairo (AUC), Semiconductor Research Cooperation, Global Foundries, the STDF, Intel, Mentor Graphics, and MCIT.

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