Design of a Compact High Performance Electro-Optic Plasmonic Switch

<table>
<thead>
<tr>
<th>Journal:</th>
<th>Photonics Technology Letters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manuscript ID:</td>
<td>PTL-29997-2015</td>
</tr>
<tr>
<td>Manuscript Type:</td>
<td>Original Paper</td>
</tr>
<tr>
<td>Date Submitted by the Author:</td>
<td>11-May-2015</td>
</tr>
<tr>
<td>Complete List of Authors:</td>
<td>Hsieh, Cheng-Hung; National Tsing Hua University, Engineering and System Science Lin, Kun-Pei; National Tsing Hua University, Engineering and System Science Leou, Keh-Chyang; National Tsing Hua University, Engineering and System Science</td>
</tr>
<tr>
<td>Key Words:</td>
<td>Dielectric-loaded plasmonic waveguide, Electrooptic effect, Optical switch</td>
</tr>
</tbody>
</table>
Design of a Compact High Performance Electro-Optic Plasmonic Switch

Cheng-Hung Hsieh, Kun-Pei Lin, and Keh-Chyang Leou

Abstract—Here we report a compact high performance electro-optic (E-O) plasmonic switch constructed in a “directional coupler” like structure, including a plasmonic waveguide and an optical waveguide, and operated around the telecommunication wavelength of 1500 nm. An organic crystal, DAST, is adopted to serve as both the E-O material of the switch and the dielectric in the plasmonic waveguide. The variation of phase matching between the two waveguides is achieved by applying a voltage as low as 22.5 V on the E-O material, so that the optical wave can be switched between the two output ports. Simulation analysis using finite element method was employed for the design of the E-O plasmonic switch. For the optimized dimensions, a transmittance up to 66% and an extinction ratio nearly 10 dB are achieved. The simulation results of response for different wavelengths show that the E-O plasmonic switch can also be operated as a wavelength-selective switch.

Index Terms—dielectric-loaded plasmonic waveguide, electro-optic effect, optical switch.

I. INTRODUCTION

SURFACE plasmon polaritons (SPPs), the electro-magnetic wave propagating along the interface between metal and dielectric as the incident wave resonates with free electrons in metal [1], have gained a great deal of attention recently because of their potential applications in nanophotonic functional devices. A variety of plasmonic devices based on SPP waveguides (SPPWG), such as splitter [2], switch [3], directional coupler [4], and laser [5], have been considered as promising candidates to break the diffraction limit of light since the optical signals could be guided and confined well at subwavelength scale [1]. However, most of the aforementioned plasmonic devices are passive ones and easily subject to the native absorption loss, limiting the performance of devices. To widen the range of applications, lots of approaches have been put forward for active control of light, such as thermo-optic effect [6], all-optical effect [7], and electro-optic (E-O) effect [3], and etc. In particular, extensive efforts have been made recently toward the development of the E-O switch due to the ability of connecting electronic communication circuits and the associated optical counterparts [8].

For the geometry of E-O plasmonic switch, four basic designs, T-shaped metal-dielectric-metal (MDM) structure [9]-[12], teeth-shaped metal-insulator-metal (MIM) structure [8], [13], vertically coupling structure [14]-[15], and dielectric-loaded plasmonic waveguide (DLW)-based structure [3], [16], have been investigated. Both the T-shaped MDM switch and teeth-shaped MIM switch [8]-[13] have been shown to have the features of compact dimension and high selectivity of coupling by employing an organic material having a large electro-optic coefficient (dn/dE), i.e., 4-dimethyl-amino-N-methyl-4-stilbazolium tosylate (DAST). A vertically coupling switch [14]-[15], which may enable a three dimensional optical communication has also been proposed. However, as a result of the low low dn/dE coefficient of the nematic liquid crystal which was adopted as the E-O material, a fairly large footprint was needed for the device for light coupling in optical integrated circuits. For the DLW-based switch [3], [16], the coupling to a waveguide ring resonator (WRR) can be controlled for wavelength selectivity, but a fairly large substrate area is needed for ring resonator structure and, on the other hand, a greater coupling transmittance, e.g., > 50%, is highly desirable for future improvement of this device.

In this letter, we propose an E-O plasmonic switch, having a structure similar to a conventional directional coupler. It consists of a dielectric-loaded plasmonic waveguide (DLW), called rounded top metal dielectric-loaded plasmonic waveguide (RTM-DLW), similar to the SPPWG reported recently [17], having features such as easy fabrication, and multiple functionalities which are made possible by selecting the suitable dielectric material [18]. The switching of the transverse magnetic (TM) mode can be achieved by the E-O effect of a crystalline organic, DAST, which has been integrated with plasmonic devices [8]-[13]. The structure and dimensions of the two coupled waveguides of the E-O plasmonic switch are chosen so that the phase matching condition can be tuned by adjusting the voltage on the DAST. Consequently, the optical wave from the input waveguide can be switched between the two waveguides, propagating toward either the cross (CRS) port or the through (TRU) port. In such a directional coupler like configuration, the switch can be made very compact while minimizing reflections caused by discontinuities seen by the propagating waves. Consequently, a transmittance of the optical waves through the switch, in principle, can be obtained, along with a high isolation between the two output ports. One potential application for the proposed E-O plasmonic switch proposed in this work is to route and switch light in the integrated photonic platforms for optical
communications [19], such as inter-chip and intra-chip interconnections [20]-[21].

II. ANALYSIS METHOD OF PLASMONIC DEVICES

Fig. 1 shows the structure of the directional coupler (DC)-based plasmonic switch proposed here, comprising a RTM-DLW, and a silicon carbide optical waveguide (SiCWG), separated by 50 nm gap. The silicon carbide (SiC) was adopted as the material of the optical waveguide, the “main” waveguide of the switch, because of a nearly zero absorption loss of SiC at the desired wavelengths [22]-[23]. The RTM-DLW, the “coupled” waveguide of the switch, composes of a top silver (Ag) stripe, a tantalum (Ta) adhesion layer and a DAST dielectric. Both waveguides are supported by a silicon dioxide (SiO$_2$) substrate coated with a silver (Ag) conducting layer (Fig. 1(a)) which serves as the bottom electrode for the E-O switch operation. A 90° bend was employed to separate the two outputs (CRS and TRU ports), as depicted in Fig. 1(b).

A finite element code, COMSOL Multiphysics, was used for the analysis of the proposed plasmonic switch. The simulation analysis was carried out first to determine the propagation characteristics of each waveguide, where both were operated under the TM mode. For a given waveguide cross section, the complex refractive index ($n$) of the desired mode, $n = n_{eff} + ik$, was solved, where $n_{eff}$ and $k$ are the effective refractive index and the extinction coefficient, respectively. The dimensions of the two waveguides were then chosen so that the phase matching condition was satisfied, i.e., the $n_{eff}$ for both the main and coupled waveguides are equal. Consequently, the optical waves propagating in one waveguide can be coupled, ideally near 100% into the other one, or, with the E-O materials, can be switched between the CRS and TRU ports, controlled by external electric field.

![Image](https://example.com/image.png)

Fig. 1. (a) Structure of plasmonic switch, comprising of RTM-DLW and SiCWG. (b) Cross-section of the plasmonic switch. The dimension of RTM-DLW and SiCWG: $R_1 = 80$ nm, $w_1 = w_2 = 2R_1$, $h_1 = 450$ nm, $t = 5$ nm, $d = 200$ nm, and $s = g = 50$ nm.

The E-O material adopted in this work, also serving as the dielectric of the RTM-DLW, is an organic crystal, DAST, having a great potential for application in active plasmonic devices because of its large electro-optic coefficient (dn/dE) of the E-O effect [8]-[13]. Due to its optical anisotropy, the light of different polarizations travels through the DAST at different velocities as a result of different refractive indices. For the largest dn/dE, the DAST is characterized by three refractive indices ($n_1$, $n_2$, and $n_3$) where $n_1 = n_0 = 2.2$, and $n_2 \sim n_3 = n_s = -1.6$ are obtained at the telecommunication wavelength of 1550 nm [13], [24]. Here, $n_s$ and $n_e$ denote the refractive index of the ordinary and extraordinary wave, respectively. Because of the large dn/dE of DAST, the effective refractive index of RTM-DLW can be manipulated easily with a low external voltage. To simplify the analysis in numerical simulation, we assumed that the polarization of the TM mode optical wave was oriented to experience only a specific refractive index ($= n_1$), the largest one, and also the component controlled by the external electric field. The effect of the other refractive indices was assumed to be negligible since the fraction of electric field energy in other components is usually minimal. The effective refractive index of DAST could be determined by an external electrostatic field (voltage), given by [25],

$$\frac{dn}{dE} = n_0 + \frac{dn_{eff}}{dE} \cdot E_{ext}$$

(1)

where $dn/dE = 3410$ pm/V [26], and $E_{ext}$ is the external electrostatic field. For the E-O plasmonic switch proposed here, the external voltage was applied on the rounded metal of RTM-DLW while the bottom conducting film was grounded, as shown in Fig. 1(b). The properties of the materials at the wavelength of 1550 nm in the simulation are given in Table I.

<table>
<thead>
<tr>
<th>MATERIALS</th>
<th>$\varepsilon_1$</th>
<th>$\varepsilon_2$</th>
<th>$\varepsilon_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>2.08</td>
<td>6.60</td>
<td>5.20</td>
</tr>
<tr>
<td>SiCWG</td>
<td>5.20</td>
<td>-129.0</td>
<td>-71.71</td>
</tr>
<tr>
<td>DAST</td>
<td>3.29</td>
<td>14.89</td>
<td>-</td>
</tr>
<tr>
<td>Ta</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

III. SIMULATION RESULTS AND DISCUSSION

The dimensions of the RTM-DLW were chosen to obtain a long propagation length while maintaining a small mode area, as given in our previous work [17]. The thickness of Ta, Ag, and DAST are 5, 200, and 450 nm, respectively, as shown in Fig. 1(b), and the radius ($R_I$) of rounded corner of Ag strip is 80 nm. For a better phase matching and a high coupling efficiency of the switch, the height of the SiCWG is the same as that of the DAST dielectric of the RTM-DLW. We first determined the propagation characteristics of each waveguide separately by solving the eigen-modes of the waveguide using the COMSOL Multiphysics code, and the results are shown in Fig. 2(a), where the effect of waveguide width on $n_{eff}$ for the TM mode are illustrated. From the simulation results, for our initial design, the widths of the RTM-DLW and the SiCWG are 800 and 450 nm, respectively, so that, when the external voltage/electrostatic field is on, the phase matching condition is met. For this particular dimension, the fractional difference of the two $n_{eff}$, $\Delta n_{eff}/n_{eff}$ is less than 0.002%. This dimension adopted for the two waveguides also features only single mode propagation, without interference from any transverse electric (TE) mode (results not shown). Fig. 2(b) and (c) show the corresponding cross-sectional distribution of the electric field strength of the operating TM mode for the RTM-DLW and SiCWG, respectively.

For the structure of the proposed E-O switch, the coupling length ($L_c$) for the optical waves propagating along the two waveguides plays an essential role for efficient switching of signals. Simulation analysis was then carried out for the entire E-O switch shown in Fig. 1(a), where the optical wave was launched from the left end of the main waveguide, i.e., SiCWG. From the simulation results, the propagation powers at the input, CRS and TRU ports, i.e., $P_{in}$, $P_{CRS}$, and $P_{TRU}$, respectively, were calculated by integrating the Poynting vector...
over the corresponding cross section of each port. Two fundamental parameters characterizing the performance of the switch, insertion loss (IL) and isolation (I), are then determined. The insertion loss for the CSR and TRU ports are defined as a ratio of \( P_{\text{CSR}} \) to \( P_{\text{in}} \) (\( IL_{\text{CSR}} = 10 \log_{10}(P_{\text{CSR}}/P_{\text{in}}) \)) and \( P_{\text{TRU}} \) to \( P_{\text{in}} \) (\( IL_{\text{TRU}} = 10 \log_{10}(P_{\text{TRU}}/P_{\text{in}}) \)), respectively, where the power ratio of output (\( P_{\text{CSR}} \) or \( P_{\text{TRU}} \)) to input (\( P_{\text{in}} \)) is defined as a transmittance (\( T \)). Then, the corresponding isolation between the two ports is given by \( I = IL_{\text{CSR}} \times IL_{\text{TRU}} \). and \( IL_{\text{TRU}} \times IL_{\text{CSR}} \) for switch off and on, respectively. Fig. 3 shows, when the applied voltage on the E-O plasmonic switch is off and \( R_c = 1.6 \mu m \), the dependence of the insertion losses and the corresponding isolation on the coupling length, \( L_c \), which can be varied by varying the gap between the two waveguides. The results in Fig. 3 show that the minimum \( IL_{\text{TRU}} \) occurs for \( L_c = 7 \mu m \), while the \( IL_{\text{CSR}} \) seems not sensitive to \( L_c \) when \( L_c < 8.5 \mu m \), and the resulting peak \( I \) is 9.0 dB. Please note that, for the analysis and results presented in the followings, the coupling length is chosen to be \( 7 \mu m \) with the radius of the 90° bend \( R_c = 2 \mu m \), which has been optimized to maximize the isolation, yielding \( I = 9.6 \) dB (results not shown).

It is also important to note that the overall size of this E-O plasmonic switch, \( L_c + R_c - w_j = 9.8 \mu m \), is smaller than that of the waveguide ring resonator (WRR)-based switch, \( \sim 11 \mu m \), reported in previous studies [3], [16], and, at the same time, achieving a transmittance of 64% (corresponding to \( IL_{\text{CSR}} = -1.9 \) dB), an increase of 48% compared to that for the WRR-based switch (\( \sim 43% \)) [3], [16].

The phase matching can be modified [26] by changing the relative permittivity, and the corresponding \( n_{e} \) of the RTM-DLW by varying the voltage applied between its top and bottom Ag stripe/layer. In the simulation using COMSOL Multiphysics when an external voltage was applied, electrostatic analysis was first carried out to determine the electrostatic field distribution in the E-O material (DAST) and then the local electric field was used in eq. (1) to obtain the corresponding local \( n_{e} \), which was subsequently used as the input for the electromagnetic simulation of the propagation of optical waves. Fig. 4(a) depicts the ILs and \( I \) for different external voltage (\( V_{DC} \)) on the Ag stripe of RTM-DLW, as shown in Fig. 1(b). The simulation results show that, as \( V_{DC} \) increases, the \( IL_{\text{CSR}} \) decreases while \( IL_{\text{TRU}} \) increases due to a rising phase mismatching between the main/coupled waveguides. Therefore, to obtain \( I > 10 \) dB, one needs \( V_{DC} \geq 22.5 \) V, a value comparable to that of other E-O plasmonic switches [8], [9], [13]. Fig. 4(b) shows the cross-sectional distribution of the electrostatic field strength for \( V_{DC} = 22.5 \) V obtained from the electrostatic calculation by COMSOL Multiphysics. It is important to note that, for the switch on state, i.e., \( V_{DC} = 22.5 \) V, a transmittance of 66% (corresponding to \( IL_{\text{TRU}} \) of \(-1.8 \) dB) is achieved, much larger than that of other DAST-based E-O plasmonic switches (56% \(-20\% \)) [8]-[13] by a factor of 17% \(-230\% \). Fig. 4(c) and (d) shows the power density of the optical waves at 1550 nm wavelength propagating along the two waveguides, demonstrating the switching of optical waves between the CRS and TRU ports, for \( V_{DC} = 0 \) V and 22.5 V, respectively.

Fig. 5(a) and (b) illustrates the effect of wavelength on the \( IL_{\text{CSR}} \), \( IL_{\text{TRU}} \), and the corresponding \( I \) and extinction ratio (ER), respectively, when the E-O switch is off (\( V_{DC} = 0 \) V) and on (\( V_{DC} = 22.5 \) V). The \( ER \) is defined as the ratio of transmittance at the output port in the states of \( V_{DC} = 0 \) V and \( V_{DC} = 22.5 \) V, i.e., \( 10 \log_{10}(T_{\text{ON}}/T_{\text{OFF}}) \) and \( 10 \log_{10}(T_{\text{OFF}}/T_{\text{ON}}) \) for CRS and TRU ports, respectively [9]. For switch off (on), i.e., \( V_{DC} = 0 \) (22.5) V, the spectrum in Fig. 5(a) shows the \( IL_{\text{CSR}} \) (\( IL_{\text{TRU}} \)) larger than \(-2.0 \) dB as the associated \( IL_{\text{TRU}} \) (\( IL_{\text{CSR}} \)) is less than \(-10 \) dB, at the wavelength of 1550 nm. As a result, the corresponding \( I \) is \( > 9.5 \) dB and the resulting \( ER_{\text{TRU}} \) and \( ER_{\text{CSR}} \) are both larger than 9.7 dB, demonstrating the optical waves can be switched efficiently between the two output ports, with quite small loss for both on/off states. On the other hand, the
results in Fig. 5(b) reveal that the switch also has a great potential to switch signals of different wavelengths since the optimal ERs are obtained, > 13 dB, for 1500 and 1650 nm wavelength at CRS and TRU ports, respectively. These results demonstrate that the E-O plasmonic switch proposed in this work can be a highly efficient switch in the optical communication systems [29].

Fig. 5. The spectrum of (a) IL_{CRS} vs. Wavelength (nm) and (b) IL_{CRS} vs. ER_{RUS} for switch on and off. The other dimensions of the switch are identical to those in Fig. 4.

IV. CONCLUSION

In this letter, we proposed a directional coupler like E-O plasmonic switch for switching of optical waves at telecommunication wavelength between two output waveguides. A DLW-based coupled waveguide, where an organic DAST serving both as the waveguide dielectric as well as the E-O switching material, was chosen so that the effective refractive index of the RTM-DLW, and the resulting phase matching condition can be efficiently varied while maximizing the transmission efficiency of the E-O switch. For the optimized dimensions, simulation results show that a transmittance ≥ 64% of optical waves to either output ports with an isolation of ≥ 10 dB, as the E-O switch is on or off, can be achieved. Because of the high E-O coefficient of the DAST as well as the directional coupler like structure, a low operation voltage of 22.5 V is needed for the proposed E-O switch. Moreover, a high extinction ratio for both output ports, ~10 dB, has also been obtained, demonstrating the superior performance of the proposed E-O plasmonic switch. On the other hand, the high isolation (>10 dB) for both on and off states would enable the E-O switch as a potential candidate for a two-way plasmonic switch suitable to serve as an active coupler between the plasmonic devices and conventional photonic integrated circuits. The E-O plasmonic switch proposed here can also be operated as a wavelength-selective switch, as demonstrated from the spectral response of the switch.

REFERENCES