International Journal of Engineering and Advanced Technology (IJEAT)
ISSN: 2249-8958 (Online), Volume-8 Issue-6, August, 2019

# An Ultra-CompactOptical Modulator using Indium Tin Oxide Materialand Metal-Dielectric-Metal Waveguide Structure.

**Tanvi Vaidya, Diksha Chauhan, Hyoung In Lee, Chongmu Lee, Ram Prakash Dwivedi**

***Abstract: These days Ultra-compact modulators are seeking so much interest in their research area, because these are the main components of optical transmission systems and also Ultra-compact and ultra- high speed semiconductor electronic modulators are very significant for optoelectronic integrated circuits. The resonant modulators can be of very small size therefor we have proposed a compactIndium Tin Oxide (ITO) based Opto- Electronic Modulator in a Metal-Dielectric-Metal Plasmonic Waveguide Structure and utilizing resonance property in the device. The device has dimension of 0.01 $\mu m^3$ and shows modulation depth approximately 9 dB near telecommunication wavelength of 1.5 $\mu m$. All the calculations had been done using Finite Element Method (FEM). We have also studied the applications of the device as a tunable filter near the telecommunication wavelength. Performance of the suggested device is quite acceptable with comparison to device size and considered valuable for photonic integrated circuit.***

***Index Terms: Plasmonics, MDM waveguide, ITO, Modulator***

## I. INTRODUCTION

In Plasmonics, it is possible to integrate two most important technologies: Nano electronics and ultrafast photonics [1,2]. Metal- dielectric interface supports plasmonic waves because these waves are closely coupled to the interface and allowstransmission of light at the nanoscale. Plasmonics are the leading technologies for a new generation of fast and on-chip nano devices with exceptional capabilities. We require some devices such as amplifiers, photo detectors, modulators and light sources for the basic functionality of nano photonic circuitry. For highest mode localization and minimum propagation loss, several designs of plasmonic waveguide structures had been described earlier [3, 4]. Among them waveguide having a dielectric layer sandwiched between two metal layers is very useful as it reduces the size of the device and provide high field confinement [5]. Cutoff does not occur in metal-dielectric-metal (MDM) wave guiding structure even at very small dielectric layer thickness so this structure allows very thin layouts of tens of nanometer [6].

Revised Manuscript Received on October 30, 2019.
* Correspondence Author
**Tanvi Vaidya*.** School of Electrical and Computer Science Engineering, Shoolini University, India.
**Diksha Chauhan.** School of Electrical and Computer Science Engineering, Shoolini University, India.
**Hyoung In Lee.** Research Institute of Mathematics, Seoul National University, Korea.
**Chongmu Lee.** Department of Material Science and Engineering, Inha University, Korea.
**Ram Prakash Dwivedi.** School of Electrical and Computer Science Engineering, Shoolini University, India.



These possess many symmetrical and asymmetrical modes as well as quasi- bounds and metal-clad, depending on the frequency range [8]. Ultra-compact and very high speed semiconductor electronic modulators are very significant for a chip scale, high density optoelectronic integrated circuits. Speed and bandwidth of signal depends on the modulator type i.e. whether a resonant or non-resonant modulator is used [18]. Resonant modulators quality factor (Q) depends upon design, e.g. micro-rings and micro-disks [10], photonic-crystal cavities, stub structure [16] etc. Thus, resonant modulators can be compact sized and have a very high speed and modulation strength. Ultra-compact modulators are seeking so much interest in research field because these are the main components in optical transmission links and also resonant modulators can be of very small size. Many reports have been stated about plasmonic modulation based on different active tuning mechanisms such as elasto-optic effect and phase transition phenomena [9-11]. However, the modulation concept stated earlier in these mechanisms requireda large device areal footprint and high bias voltage, andthese devices can also exhibit a high device loss. Here an ultra-compact optical modulator with small voltage requirement and low device loss is proposed. Transparent conducting oxide (TCO) is used as an active material to design an ultra-compact modulator. In particular, we have taken Indium-Tin-Oxide (ITO) layer as TCO,which is inserted between two metal layers in the suggested device. Incredible tuning and modulation can be attained using ITO, because by applying electric field, a change of several orders of magnitude of carrier concentration of ITO can be attained [12]. Therefore for increasing electro-optical abilities ofelectro- optic devices, ITO is a promising material. There are reports on design of plasmonic modulators using ITO in MDM wave guiding structure too [13, 14]; however, up to our knowledge, plasmonic modulator using ITO in MDM waveguiding structures utilizing an ultra-small gap structure is not yet reported. The gap structure in this designed device generates resonance spectrum in the output, which subsequently improves the efficiency of the modulator. In the output of the device, the resonance property for designing ultra-compact optical filter can also be used, which is also the part of our study.

## II. DESIGNS AND THEORY

Fig. 1(a) shows block diagram of ultra-compact plasmonic modulator containing $SiO_2$ layer and ITO layer with a gap of length L in a MDM waveguide structure.

The purpose of gap Lis to generate resonance in the output of waveguide and to reduce the size of modulator using resonance property. Fig. 1(b) and (c) shows the side view of MDM waveguide indicating the change in effective index with and without application of electric field. Change in overall effective index is due to accumulation of charge particles at the ITO/$SiO_2$ interface caused by the application of electric field across MDM waveguide

When we incident light at one end of MDM waveguide then light wave propagates through plasmonic waveguide [15]. The dispersion relation of the fundamental TM mode in an MIM waveguide is given as

$$\epsilon_{in}\, k_{z2} + \epsilon_m\, k_{z1} coth\left(-\frac{ik_{z1}}{2} w\right) = 0 \text{----(1)}$$

With$k_{z1}$ and $k_{z2}$ defined by momentum conservations

$$k_{z1}^2 = \epsilon_d\, k_0^2 - \beta^2, k_{z2}^2 = \epsilon_m\, k_0^2 - \beta^2 \text{----- (2)}$$

Where$\epsilon_d$ and $\epsilon_m$ are, dielectric constants of the dielectric and the metal respectively, and $k_0 = 2\pi/\lambda_0$is the free-space wave vector. The effective index of plasmonic waveguide is given by $\eta_{eff} = \beta/k_0$, where $\beta$ represents the propagation constant of waveguide.

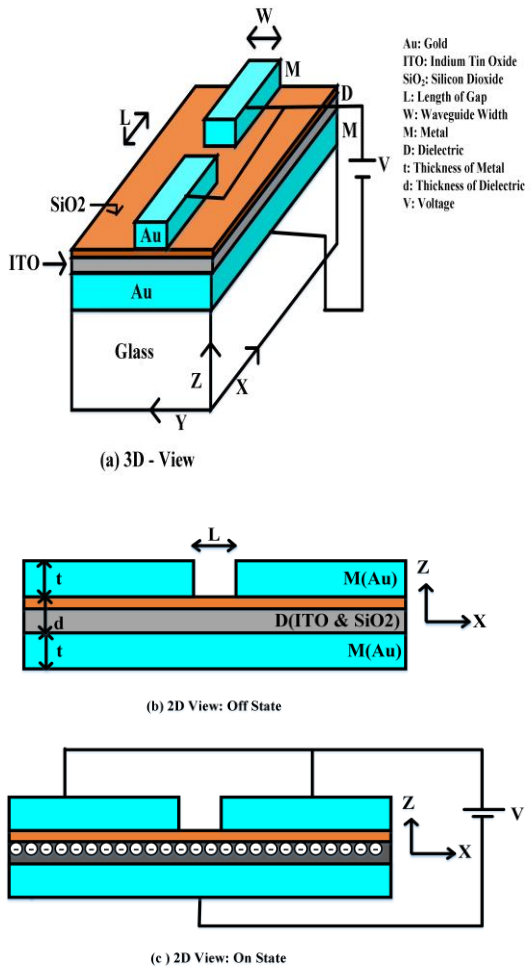



**Fig. 1:** (a) Block diagram of the designed device in three dimensional view (b) Two dimensional view of device without electric field (c) shows mechanism of accumulation of charge carries with electric field application.Here we propose ITO as an active material and inserted a layer of ITO within the waveguide. When bias is applied, it results an electric field across the ITO layer due to which modulation is achieved. Due to this electric field, charge accumulates near the ITO and $SiO_2$ intersection (depending upon the direction of electric field) and forms an accumulation or depletion layer near the intersection. These accumulated charges change the plasma frequency of ITO and its permittivity. According to the Drude-Lorentz model [12]:

$$\Delta n_{index} = \frac{-e^2\lambda_0^2}{8\pi^2 c^2 \epsilon_0 n_{index}}\left(\frac{\Delta n}{m_e^*} + \frac{\Delta p}{m_h^*}\right) \text{------ (3)}$$

We can form an accumulation layer in MOS devices.In thisequation effective masses of electrons and holes are represented by $m_e^*$ and$m_h^*$respectively; $\Delta n$ and $\Delta p$ represents the changes in electron and hole concentrations respectively, which induces a change in index of refraction, $\Delta n_{index}$.

The extinction ratio of modulation ($R$) is given as:

$$R = 10 \log \frac{P_2}{P_1} dB \text{------ (4)}$$

Where $P_1$ and $P_2$ are the resultant output powers in the switch-off and the switch-on states, respectively. $R$ shows how strongly the mode of propagation can be varied through waveguide. The attenuation loss ($A$) of modulator can be given as

$$A = 10 \log \frac{P_{in}}{P_{out}} dB \text{------ (5)}$$

Where $P_{in}$ and $P_{out}$ are the input and output powers measured at the ports, respectively, when power propagation through waveguide is maximum.

In the designed structure we introduced a very small gap G in MDM waveguide and get resonance output in our simulation results. The resonance phenomenon for the proposed design can be explained with the help of scattering matrix theory [15]. According to this theory, the transmittance T due to gap G in MDM waveguide is given by:

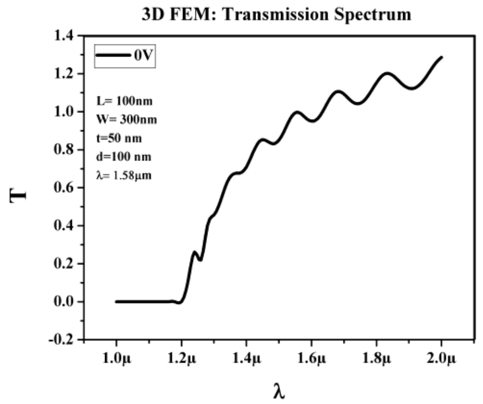
$$T = \left|\frac{E_2^{out}}{E_1^{in}}\right|^2 = \left|t_1 + \frac{s_1 s_3}{1 - r_3 exp(i\phi(\lambda))} exp\big(i\phi(\lambda)\big)\right|^2 \text{------- (6)}$$

Where $r_i$, $t_i$ and $s_i$ ($i$=1,2, 3) are the reflection, transmission, and splitting coefficients of an incident beam respectively.In the above equation, if $\phi(\lambda) = (2m+1)\pi$ where $m$=0, 1, 2,…, then the terms inside the modulus sign on the right side of the equation will cancel out each other, so that the transmittance T will become minimum. More detail about change in refractive index/carrier concentration in accordance to applied voltage and resonance theory due to gap structure has been explained in reference [16] and [15] and therefore we are not emphasizing much on detailed theory of above phenomena.

## III. RESULTS

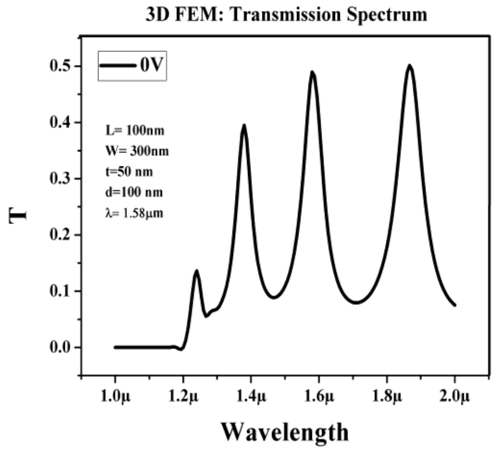
In the proposed design, we have used finite element methods (FEM) for simulation results. We solve for the E-field in the entire structure and $E_z$-field patterns are obtained at the center of the dielectric layer in the z-direction, where $z$=0. In the simulation, the permittivity of the silver metal film is taken to be -143+j*4.59 at the wavelength $\lambda = 1.55\ \mu m$[17] and refractive index of $SiO_2$ are taken as 1.5. The effectiveindex of ITO material isflexible which depends on applied voltage across MDMwaveguide.Further, thickness of metal film in MDM waveguide is 100 nm,whereas thickness of ITO/$SiO_2$ layer is 70/30 nm. The width of waveguide in every caseis 0.5 $\mu m$. Boundary integrations were performed to determine the input and the output powers.

To envision the wave transmission, FEM simulations using three-dimensional RF module and EM Waves in Harmonic Propagation Analysis are performed. In Fig. 2, we have obtained the simulation results. We had studythe effect of gap on output spectrum and measure the electric field pattern in on and off state. We had also check the influence of applied electric field on resonance peak.

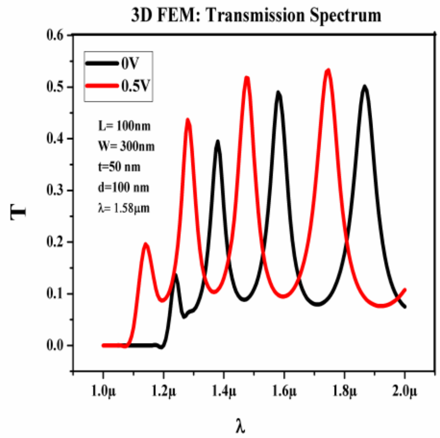



**(a)**

**Fig. 2: (a) wavelength spectrum without introducing a gap structure**



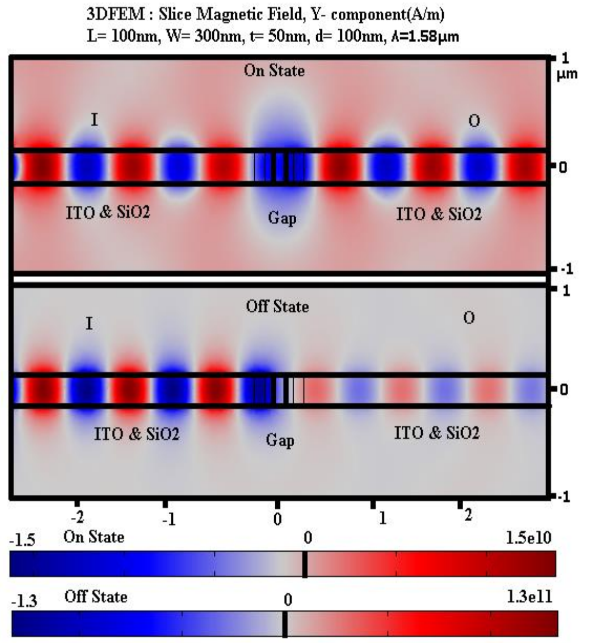

**(b)**




**(c)**

**Fig. 2: (b) wavelength spectrum after introducing a gap structure in MDM waveguide (c) wavelength spectrum in absence and presence of electric field**

Fig. 2(a) shows the output spectrum when we have not introduced the gap structure in MDM waveguide. We can see that in this case, there is no resonance in the output. When we use a gap structure in the MDM waveguide, we find a resonance spectrum in the output, which is shown in Fig. 2(b). Hence we can conclude that the resonance spectrum is due to the presence of gap structure in MDM waveguide. Further, we obtain the shifting in peak of resonance output when we change the refractive index of ITO material in simulation program. We assume that refractive index of ITO material changes when an electric field is applied across the metal electrodes of MDM waveguide. We measure the resonant spectrum together in presence and absence of applied voltages shown in Fig. 2(c). We find that there is enough shifting even with application of very small voltage. We can also see in Fig. 2(c) that at wavelength of $1.58\mu m$, minima of 0 V lies on maxima of 0.5 V, which can be used in switching or modulation of the device.




**(d)**

**Fig. 2: (d) electric field pattern in absence and presence of applied voltage.**

In Fig. 2(d), we show the top view of electric field pattern at $\lambda = 1.58\mu m$, on application of 0V and 0.5V field across the metal electrode of MDM waveguide. We can see that there is a large power in the output in case of 0.5V and very small output power in case of 0V. This is due to resonance in the output of the device. From Fig. 2(d), when we compute the modulation ratio using Eq. (4), we found that it is approximately 6.9dB. This is quite acceptable value for such a small size device.

## IV. DISCUSSION

In the charge accumulation layer, change in carrier concentration is very fast due to phase transition phenomenon, and thus the opto-electronic modulators can achieve very fast operation speed in hundreds of giga hertz. Consequently, it requires long propagation distances to accumulate the sufficient phase or absorption changes, which results in increased size of devices up to hundreds of micrometers.

These days TCOs are promising materials for providing electro-optical capabilities to ultra-compact plasmonic devices. We have just taken arbitrary parameters for length, width, thickness and length of resonant gap. We have not explored the optimization of these parameters till now. We still believe that by optimizing these parameters, we can get much better result. This tunability combined with the fact that silicon and TCOs are already used in an enormous array of applications makes these technologies ideal candidates for integrated optical systems. Resonant structure of modulator reduces the size of device and improves the efficiency, whereas stronger or sharper the resonance, the narrower is the device's operational bandwidth. We have observed that the device loss is larger due to metal electrodes; however, device size is so small that a small loss could be accepted. We have seen that enough change in output power is obtained with very small change in voltage. This might be one of the significant achievements of the designed device.

## V. CONCLUSION

In this study, we presented that ITO can be used as an active material in MDM waveguide, and are useful materials for active plasmonic devices. The operation of proposed device is based on modulating the carrier density distribution within a MDM waveguide. In comparison to size, the device has quite acceptable modulation ratio. Due to resonance property, the device can also be used as optical filter. Since peak of resonance changes when voltage is applied and therefore it can be used as tunable filter.

## ACKNOWLEDGEMENT

This work has been supported by Shoolini University. We also acknowledge the motivation given by Prof. El-Hang Lee during my PhD in his supervision.

## REFERENCES


1. Dionne, J.A., Atwater, H.A.: 'Plasmonics: Metal-worthy methods and materials in nano photonics', MRS Bulletin, vol. 37, 2012, pp 717-724.
2. Brongersma, M.L. and Shalaev, V.M.:'Applied Physics: The case for plasmonics', Science, vol. 328, 2010, pp 440-441.
3. Dmitri, K.G., Sergey, I. B.: 'Plasmonics beyond the diffraction limit', Nature Photonics, vol. 4, 2010, pp83-91.
4. Dionne, J. A., Lezec, H. J., Atwater, H. A.: 'Highly confined photon transport in sub- wavelength metallic slot waveguides', Nano Lett., vol. 6, 2006,pp 1928–1932.
5. Zia, R., Selker, M. D., Catrysse, P. B., Brongersma, M. L.: 'Geometries and materials for sub-wavelength surface plasmon modes', Journal of the Optical Society of America A, vol. 21, 2004,pp 2442-2446.
6. Kurokawa, Y., Miyazaki, H.T.: 'Metal-insulator-metal Plasmon nanocavities: Analysis of optical properties', Physical Review B, vol. 75, 2007,pp 035411.
7. Liu, Y., Kim, J.: 'Numerical investigation of finite thickness metal–insulator–metal structure for waveguide-based surface plasmon resonance bio-sensing', Sensors and Actuators B, vol. 148, 2010, pp 23-28.
8. Chen, J., Smolyakov, G.A., Brueck, S. R, Malloy, K. J.: 'Surface plasmon modes of finite, planar, metal-insulator-metal plasmonic waveguides', Optics Express, vol. 16, 2008,pp 14902-14909.
9. Dwivedi, R.P., Lee, H.S., Song, J.H., An, S., Lee, E.H.: 'Plasmonic Modulator utilizing three parallel Metal-Dielectric-Metal Waveguide Directional Coupler and Elasto-optic Effects', Optics Communications, vol. 284, 2011, pp 1418–1423.
10. Dwivedi, R.P., Lee, E.H.: 'A Compact Plasmonic Tunable Filter using Elasto-optic Effect', Optics and Laser Technology, vol. 44, 2012, pp 2130-2134.
11. Dwivedi, R.P., Sharma, D., Lee, C., Vaidya, T.: 'A Plasmonic Switch using Metal Insulator Transition in $VO_2$' ,Journal of Optoelectronics and Advanced Materials, vol. 18, 2016, pp 207-212.
12. Feigenbaum, E., Diest, K., Atwater, H.A.: 'Unity- order index change in transparent conducting oxide at visible frequencies', Nano Letters, vol. 10, 2010,p 2111-2116.
13. Babicheva, V.E., Kinsey, N., Naik, G.V., *et al.*: 'Towards CMOS-compatible nanophotonics:Ultra-compact modulators using alternative plasmonic materials', Optics Express, vol. 21, 2013,pp 27326-27337.
14. Schuller, J.A., Barnard, E.S., Cai, W., Jun, Y.C., White, J.S., Brongersma, M.L.: 'Plasmonics for extreme light concentration and manipulation', Nature Materials,vol. 9, 2010,pp 193.
15. Boltasseva, A., Bozhevolnyi, S.I.,Nikolajsen, T., Leosson, K.: 'Compact Bragg gratings for long-range surface plasmonpolaritons', Journal of Lightwave Technology, vol. 24, 2006, pp912.
16. Lin, X.S., Huang, X.G., 'Tooth-shaped plasmonic waveguide filters with nanometeric sizes', Optics Letter, vol. 33, 2008,pp 2874.
17. Song, J.H., Lee,H.S., Hoan, O., Lee,S.G., Park, S.G., Lee, E.H.:'Design of nanoring resonators made of metal–insulator–metal nanostrip waveguides', Journal of the Korean Physical Society, vol. 6, 2010, pp 1789–93.
18. Xu, Q., Schmidt, B., Pradhan, S., Lipson, M.: 'Micrometer-scale silicon electro-optic modulator', Nature,vol. 435, 2005,pp 325-327.