Metal-insulator-metal waveguide based plasmonic sensors: Fantasy or truth- A critical review

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October 28, 2022

Abstract

There is a hysteria over plasmonic sensors based on Metal-insulator-metal (MIM) waveguides and researchers around the globe are extensively studying these devices over the past two decades for diverse sensing applications for instance temperature, refractive index, pressure, and biochemical applications among others. The sensors based on MIM waveguides (WGs) are compact and offer unmatchable sensitivity as assessed with dielectric waveguide-based sensors along with an extraordinary figure of merits (*FOM*). However, the major concern is that most of these sensors are only numerically simulated/analyzed and there is no experimental demonstration accessible to date. Therefore, in this mini-review, these highly alluring sensor designs are critically analyzed to identify if they are practically feasible or just a fantasy among the scientific community.

Introduction

The study of surface plasmon polaritons (SPPs)-based nanophotonics has rapidly increased over the past two decades. Well beyond the diffraction limit, these electromagnetic (EM) waves can be steered by metallic nanostructures as they travel over metal-dielectric surfaces. The progress of highly integrated photonic signal-processing systems, sensors, and optical imaging techniques with nano resolution are all made possible by these extraordinary capabilities. Thanks to their special qualities, plasmonic-based devices have attracted a lot of attention in recent years, significantly increasing the sensitivity of photonic sensors. Expectations regarding the role of metals in the creation of novel optical devices based on plasmonic phenomena, including SPPs, are being changed by ongoing advances in nanofabrication. These have potential applications in a variety of fields, including nanophotonics, biosensing, electronics, imaging, and many more.

Among other plasmonic waveguides, metal-insulator-metal (MIM) WG architecture is one of the most widely utilized plasmonic-based nanostructures for the creation of integrated optical circuits. MIM WGs are plasmonic structures that have two metal claddings around an insulator as shown in Figure 1 (a). The primary characteristics of this system are its straightforward construction and potential to restrict light at the sub-wavelength level. The E-field distribution taken at the output of the MIM WG is shown in Figure 1 (b). The light injected in this WG propagates in the air and is fully exposed to the ambient medium. When there is a slight change in the refractive index in the ambient medium, this brings a large shift in the effective index of the propagating mode as shown in Figure 1 (c). Another appealing plasmonic WG structure that has been employed in both active and passive devices is an insulator-metal-insulator (IMI), which sandwiched metal between two insulator claddings. Since IMI WGs have substantially lower propagation losses than MIM WGs, they are often utilized to transmit near-infrared optical power across distances greater than 10 μm. A TM mode that is equal to a dielectric mode can be sustained if the symmetry criterion is strictly satisfied. However, its use is constrained at deep subwavelength scales due to the absence of mode confinement.

Heisenberg's uncertainty principle states that further reduction in the dimension of dielectric WGs will inevitably result in cut-off because the mode size of a dielectric WG is affected by the diffraction limit (close to λ/2n, where n is the refractive index of the core and λ is the incident wavelength in a vacuum). The size of the focused point was shown to be almost directly related to the radius of the nanosphere. Thus, when the radius of the silicon nanosphere is 2 nm, light is constrained to a focused point with a size of λ/373. Due to this restriction, novel WG structures and materials are being investigated. The light may be contained on a deep subwavelength scale by WGs based on surface plasmons (SPs) that can sustain a propagation mode that is closely coupled to metallic surfaces. As a result, plasmonics has drawn a lot of interest due to their potential for overcoming diffraction limitations. To further identify the optical characteristics of plasmonic systems, theoretical, computational, and numerical simulation tools like COMSOL and Lumerical have been developed. The rapidly growing discipline of plasmonics combines basic study with practical applications in physics, engineering, chemistry, biology, food science, medicine, and environmental sciences.

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Figure 1. (a) 3D model of a MIM WG structure, which constitutes a thin metal film deposited on a substrate. And a narrow slit (few nm) is inscribed in the thin-film which provides a way for the SPP to propagate in a low-index medium, (b) a cross-sectional view of the E-field distribution taken at the output of the MIM WG, (c) The relationship between the real part of the effective index and the ambient refractive index.

In this mini-review, the recent advances in MIM WG-based plasmonic sensors are investigated and trying to figure out the possible causes which limit the experimental demonstration of such attractive devices. To the best of the author's knowledge, almost all the reports are devoted to the numerical analysis of the nanoscale sensing devices without addressing the real challenges that can arise during nanofabrication, sensing mechanisms (by using microfluidic channels), and optical characterization. There are more than ˜6000 reports published up till now on MIM WG devices indexed in the Scopus database. Butt et al. have also published more than 30 papers on the numerical study of the MIM WG-based plasmonic sensors. Most of the MIM WG-based sensors are based on unique resonant cavity schemes (as discussed later) where the gap between the bus WG and the cavity is ˜10 nm-50 nm, furthermore, the additional geometric parameters such as the width of the bus WG, defects or baffles are also in nm scale. This raises a question on the method of fabrication, reproducibility, and light coupling methods during device characterization.

High-performance plasmonic sensor designs and sensing applications

In the past two decades, MIM plasmonic WG devices are numerically simulated for temperature, refractive index, pressure, filtering, and biochemical sensing applications. Since they may be used to monitor solution concentration and pH level, as well as other biological and chemical parameters, refractive index sensors have been the subject of much research. By stimulating the sensing element with light that creates SPs that are focused on the metal's surface, an EM field is created. The MIM WG's effective refractive index (n_{eff}) changes when a substance under examination comes into connection with the sensor, which causes resonance wavelength to experience a redshift. Several vital factors must be considered while designing sensing devices. The ability to recognize variations in the ambient refractive index is the most often employed performance trait of plasmonic sensors. This is frequently expressed in terms of the bulk refractive index sensitivity (S), which is defined as:

S =[?]λ_{res}/[?]n,

where [?]λ_{res} is the change in the wavelength at which SP is excited and [?]n is the change in the ambient refractive index. A plasmonic sensor's capacity to detect slight variations in the refractive index is directly related to S and, additionally, contrariwise proportional to the width of the resonant feature (spectral dip or peak=$FWHM$) being recorded. The aggregate of these variables is frequently described as the figure of merit (FOM) and is stated as:

$FOM = S / FWHM$,

Even though the *FOM* is quite high in certain articles, it is interpreted in a different way in each work and is typically described to as *FOM*.* For example, in , a great value of*FOM* *=2.33×10^4 is derived by means of the formula [?]R/(R[?]n) at a constant wavelength, where R is the reflection rate in the sensor structure and [?]R signifies the fluctuation in reflection intensity caused by changes in the ambient refractive index ([?]n). *FOM** =4.05x10^4 is achieved in by utilizing the equation [?]T/T[?]n, where T stands for the transmittance in the suggested structures and [?]T/[?]n for the transmission shift at a fixed wavelength brought on by a change in refractive index.

A discrete state and a continuous state can couple and interfere with one another, leading to a phenomenon known as Fano resonance . In metallic nanostructures, Fano resonance has been investigated as the ideal property for bypassing the diffraction limit of light brought on by SPPs . To create Fano resonance, many plasmonic structures, including rectangular cavities , plasmonic nanoclusters , nanoslits , and MIM WG structures , have been suggested. Because of the abrupt and asymmetric line structure of plasmonic sensors based on Fano resonance, which allows the transmission spectrum to be quickly lowered from peak to trough, it is predicted that these sensors will be very sensitive. The transmission spectrum's *FWHM* is quite small, which greatly enhances the sensor's detecting resolution. A few of the several Fano resonance-based refractive index sensor architectures that have been published in 2022 are stated here. In terms of *FOM* , Fano resonant systems may be superior to the more traditional Lorentz resonant systems; however, the systems' ability to translate improvements in*FOM* into the ability to detect smaller changes in the bulk refractive index may be constrained by the insufficient contrast of plasmonic spectral features.

Figure 2 demonstrates the several designs of the MIM WG-based plasmonic sensors employed for refractive index and temperature sensing applications that are numerically investigated by the researchers. Several reports proposed a use of defects, baffles, and nanodots as a mechanism to enhance the sensitivity by narrowing down the path of the SPs which results in the enhanced light-matter interaction. However, this requires extremely high-resolution lithographic process and precise etching of the unwanted metal layer to create such designs. The sensing performance of all the devices is extremely high, however, none of the researchers have studied the mechanism of light coupling and the losses associated with it to such nanoscale WGs. Therefore, how many of these sensor designs can be practically realizable is a tough question for the experimental groups to obtain devices with sub-nanoscale footprints. Moreover, electron beam lithography (EBL) is specifically used to pattern nanoscale structures. The main benefit of EBL is that it has a sub-10 nm precision for writing customized patterns. Due to its high resolution and slow throughput, this type of direct writing is only appropriate for the creation of photomasks, small quantities of semiconductor devices, and research and development. Table 1 demonstrates the sensing capabilities of some of the prominent MIM WG-based plasmonic sensing devices which are either simulated via the Finite element method (FEM) or finite difference time domain (FDTD) method. In comparison to a 3D model, almost all the researchers choose a 2D model since it requires less processing time and produces more precise results.

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Figure 2. MIM WG based plasmonic sensor designs based on different cavity shapes, (a) side coupled square cavity, (b) end coupled ring cavity, (c) asymmetric structure, (d) ring and a rectangular, (e) side coupled ring and a defect , (f) end coupled square cavity, (g) side coupled split ring cavity, (h) cavity with defect, (i) T-shaped cavity with nanorods, (j) L-shaped cavity, (k)dual hexagonal cavities, (l) side coupled ring with baffles, (m) horizontal eight shape, (n)horn shaped cavity, (o) racetrack and circular cavity.

Table 1. Sensing characteristics of MIM WG-based plasmonic sensors

Author(s)	Application	*S*	*FOM*	Demonstration	Reference
Xu et al.	Refractive index sensing	1500 nm/RIU	75	Numerical	

Author(s)	Application	*S*	*FOM*	Demonstration	Reference
Kazanskiy et al.	Refractive index and temperature sensing	700 nm/RIU and -0.35 nm/°C	21.9 and 0.008	Numerical	
Khonina et al.	Gas sensing	135.95 pm/ppm	-	Numerical	
Wang et al.	Refractive index sensing	1114.3 nm/RIU	55.71	Numerical	
Rohimah et al.	Refractive index sensing	1333 nm/RIU	5876	Numerical	
Butt et al.	Refractive index and temperature sensing	1240 nm/RIU to 1350 nm/RIU, -0.58 nm/°C to -0.64 nm/°C	18.74 to 691	Numerical	
Binfeng et al.	Refractive index sensing	1488 nm/RIU	20	Numerical	
Yang et al.	Refractive index and temperature sensing	1750 nm/RIU and 2.455 nm/°C	-	Numerical	
Palizvan et al.	Pressure sensing	16.5 nm/MPa	-	Numerical	
Wu et al.	Refractive index and temperature sensing	3460 nm/RIU and 1.36 nm/°C	-	Numerical	
Jumat et al.	Refractive index sensing	3400 nm/RIU	36	Numerical	
Butt et al.	Refractive index sensing	1065 nm/RIU	251.17	Numerical	

Are MIM WG-based plasmonic sensors practically realizable?

Semiconductors are significantly easier to microfabricate than metals especially noble metals. With the use of sputtering or evaporation methods, plasmonic metals may be deposited in vacuum environments. Deposition rates are generally restricted to less than 1 nm/s to achieve sufficient uniformity and quality. Due to the often-low necessary plasmonics structure height, the modest deposition rate is not a major issue. The electroplating process can produce faster growth rates, but the surface quality may degrade, making it unsuitable for plasmon waves. As there are few efficient ways to etch Cu, Ag, or Au, the pattern transmission from the photoresist to metals is difficult for noble metals. However, in Cl_2-based settings, Al may be plasma etched.

Plasmonic WGs are exceptionally lossy since they include metal, in contrast to dielectric WGs where the propagation loss might be negligible. Major ohmic losses that set a maximum propagation length restriction on directed SP propagation. Various geometries have been created employing arrays of nanosize dimension characteristics to compensate for these losses. As plasmonic WGs, thin metal films with a finite width embedded in a dielectric can be employed. Given that the observed propagation length for operating with light with a wavelength of 1550 nm is stated to be as long as 13.6 mm, this shape provides the best propagation results for a surface plasmon-based WG. However, in this plasmonic WG shape, the localization for both directions is on the order of a few micrometers. One can narrow the wire's width to achieve subwavelength localization and then utilize SPs to direct light beneath the nanowire.

In general, propagation loss and mode confinement reflect a trade-off in any plasmonic WG. The propagation loss increases with decreasing mode size. The modes carried by plasmonic WGs often have more complicated geometries. Therefore, assessing the mode confinement of plasmonic WGs is a difficult process. The definition of the mode region should rely on the specific application, it has been considered and agreed upon. Energy dissipation affects both plasmonic and electronic circuits. The SP propagation length, over which the SPP intensity falls to 1/e of its initial value, can be used to represent the propagation loss.**Figure 3** presents the trade-off between the device sensitivity and other major factors such as footprint, optical losses, and fabrication complexities.

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Figure 3 . Sensitivity, fabrication complications, losses, and footprint comparison of plasmonic WGs with dielectric or hybrid plasmonic WGs.

The main benefit of the plasmonic WGs is that the operational wavelength of light does not influence its size. This makes it possible to create plasmonic WGs with lengths on the order of several tens of nanometers, something that is not feasible with dielectric WGs. Additionally, exceptionally strong light confinement and effective interaction with nanomaterials that have various special properties become conceivable. A three-dimensional plasmonic mode converter is necessary since such WGs cannot readily be included in optical integrated circuits. The plasmonic WG is made up of a MIM WG, a Si-wire WG, and a plasmonic mode converter section. On an SOI substrate, the silicon ridge WG, and the silicon section of the plasmonic mode converter are constructed, followed by the formation of the metal components using electron beam lithography and evaporation. This set of procedures makes use of standard methods for fabricating nanostructures and is hence compatible with those applied to other silicon photonic devices. For device integration, this makes it possible to integrate with other optical components on the same substrate. For a MIM WG with a core size of 50 nm $\times$ 20 nm, a plasmonic mode converter with an air gap width of 40 nm has been developed as shown in Figure 4 (a). The E-field distribution in the whole plasmonic device and at different segments of the WG is presented in Figure 4 (b).

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Figure 4 . Demonstration of a plasmonic WG, (a) SEM image of the MIM WG coupled to a plasmonic mode converter, (b) E-field distribution in the plasmonic mode converter-full device (top), the E-field distribution in the different parts of the device (bottom).

The air gap width has a significant impact on the mode converter's coupling efficiency (CE). Without the air gap, good CE cannot be achieved, but the CE is significantly increased by adding a tiny air gap of roughly 20 nm. But when the air gap width rises, the CE steadily declines until it reaches the same level as when there is no air gap at a width of 100 nm. Additionally, without the airgap, the metal portion of the mode converter absorbs or scatters most of the propagating light. Most of the light is scattered when the gap is large because the side lobes of the silicon ridge WG cannot be properly drawn to the metal.

Despite its apparent simplicity, the procedure detailed here is difficult due to the positional precision needed for fabrication at a scale of ca. 20 nm or less. With the use of NTT's advanced nanostructure production methods, this procedure is feasible. The integration of WGs with a deep-subwavelength core to optical integrated circuits is made possible by the creation of the first extremely efficient 3D mode converter. This accomplishment not only reduces the size of traditional devices but also lays the path for the possible use of novel devices with never-before-seen features in conjunction with nanomaterials. It is expected that more experimental research groups will join hands to find a low-cost and easy solution for the realization of these exceptional plasmonic sensor designs which are extensively published without experimental demonstration.

Conclusion

Plasmonic sensors based on MIM WGs are exceedingly attractive due to their small footprint and can offer extremely high sensitivity which cannot be obtained with conventional dielectric WG sensors. The triumph of such devices remains in the straightforward, accurate, less complex, low-cost fabrication and its compatibility with the existing platforms. Moreover, flexible sensor designs are required where minor variations in the geometric parameters due to fabrication imperfections should not deteriorate its sensing performance. Hence, Dr. Butt, the author of this paper believes that the plasmonic mode converter proposed by Ono M et al. at NTT is valuable for the realization of such a plasmonic WG structure, however, it is still in its infancy and entails a long way to find alternate ways to ensure the reproducibility of such devices with low technology demand.

Acknowledgment

The author would like to thank the Warsaw University of Technology for continuous support in the completion of this work.

Conflict of interest: There is no conflict of interest.

Data availability statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.