Plasmonic switch based on asymmetric cavities with embedding square of gold inside the cavities

Majid Ghadrdan,1 Mojtaba Shahraki, and Mohammad Ali Mansouri-Birjandi
University of Sistan and Baluchestan, Faculty of Electrical and Computer Engineering, Zahedan, Iran

ABSTRACT. We proposed an all-optical plasmonic switch based on metal-insulator-metal structures. We used the intrinsic nonlinear properties of gold to implement the switch. The proposed switch consists of a bus waveguide side coupled with a pair of asymmetric vertical cavities. We obtained the transmission spectrum of the structure for low input intensities. The results showed that a sharp dip occurs at the wavelength of 860 nm. Due to the nonlinear properties of gold and the nonlinear Kerr effects, the proposed switch has a high transmission ratio of about 0.8 mW/μm² and a low threshold power of 0.07 mW/μm². The threshold power of the structure with and without using the gold nanostructure shows a reduction of 50%. The result showed that the proposed switch has the potential to be applied in the plasmonic integration circuits.

1 Introduction
All-optical switches are indispensable in integrated optical circuits, and are widely applied in all-optical networks.1 The proposed structures for implementing optical switches operate based on different principles with different characteristics and applications, among which, optical switches based on the excitation of surface plasmon polaritons (SPPs) have attracted attention due to their fast response time, low power consumption, and nanometer-scale.2-7 SPPs are electromagnetic waves propagating at the interface between a metal and a dielectric. In metal structures, only transverse magnetic (TM) polarization excites the SPPs. When light with TM polarization is applied to the metal structure, SPPs are excited.8,9 Add-drop filters, logic gates, multiplexers, and specifically switches are various types of plasmonic devices that attracted lots of scientist’s attention.10-15 Plasmonic switches are in the range of nanometers with fast response, low input power, and high transmission efficiency. In recent years, various switching mechanisms have been demonstrated in plasmonic waveguide-cavity coupled devices. One of the important and interesting approaches for the implementation of plasmonic switches is the optical nonlinear Kerr effect. Plasmonic switches are implemented based on cavities,16-18 Mach–Zehnder interferometers,19,20 directional couplers,21,22 and ring resonators.23-26 However, to the best of our knowledge, the implementation of a plasmonic switch using the nonlinear Kerr effect and the inherently nonlinear characteristics of the gold has remained unaddressed so far, and hence has been the focus of study in this paper. In this research, we demonstrate an all-optical switch based on the plasmonic cavity. It has the potential to be applied in plasmonic integration circuits. The switching threshold power and the transmission spectra for the plasmonic switch are achieved. The propagation of electromagnetic waves in the time domain is simulated with the finite difference time domain.27

*Address all correspondence to Majid Ghadrdan, ghadrdan@ece.usb.ac.ir

© 2023 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.JNP.17.036004] Keywords: cavity; gold nonlinear properties; nonlinear Kerr effect; plasmonic switch

Paper 23029G received Mar. 6, 2023; revised Jun. 27, 2023; accepted Jul. 11, 2023; published Jul. 21, 2023.
2 Theory and Structure

In this study, metal-insulator-metal (MIM) structures, cavities, and nonlinear characteristics of gold are employed to implement a plasmonic switch. Using high Kerr coefficient material, cavities, and inserting a piece of gold inside the cavities, result in an all-optical switch with a low power consumption and fast speed. For the first time, in addition to the material with a high nonlinear Kerr coefficient, the inherently nonlinear characteristics of the gold are the other factor used to implement a plasmonic switch. Because the high light intensity results in significant nonlinear effects in gold that might be due to the displacement of free and bonded electrons.28–33

Figure 1(a) shows the schematic view of the proposed switch comprising a bus waveguide side coupled with a pair of asymmetric vertical cavities. Also, the top view of the switch is shown in Fig. 1(b). The complex dielectric constant of silver is determined by the Drude model

$$\varepsilon_m = \varepsilon_{\infty} - \frac{\omega_p^2}{\omega^2 - j\gamma \omega},$$

where $\varepsilon_{\infty}$, $\omega_p$, $\gamma$, and $\omega$ are the relative permittivity at the infinite frequency, the plasma frequency, the electron collision frequency, and the angular frequency of the incident light wave, respectively. In this paper, the parameters are the following: $\varepsilon_{\infty} = 1.95$, $\omega_p = 1.37 \times 10^{16}$ (rad/s), and $\gamma = 20 \times 10^{12}$ rad/s, which were taken from Ref. 24.

The straight waveguide and the cavities are filled with air and the nonlinear Au/SiO$_2$, respectively. The cavities can enable deep subwavelength confinement of SPPs in all three spatial dimensions.

The dielectric in the straight waveguides is air with a refractive index $n_{\text{air}} = 1$. The dielectric in the cavities is Au/SiO$_2$ with high Kerr nonlinearity, which has a refractive index of $n_0 = 1.47$ and Kerr non-linear coefficient of $n_2 = 2.07 \times 10^{-9}$ cm$^2$/W.34 The surface plasmon resonance of Au/SiO$_2$ composite can lead to enhanced third-order optical nonlinear susceptibility.35

![Fig. 1](image-url) (a) Schematic and (b) top view of the proposed plasmonic switch.
The width of the waveguide and the width of the two asymmetric vertical cavities, $w$, are assumed to be 150 nm. Also, the distance between the cavities, $d$, is assumed to be 150 nm. A $100 \times 100$ nm square of gold is inserted inside the cavities. As shown in Fig. 1(a) the structure should be placed on a glass substrate, as this will be also the case when it is studied experimentally. To ensure the feasibility of the fabrication technology, the thickness of the substrate, silver, and $\text{Au}/\text{SiO}_2$ are taken at 100, 50, and 50 nm, respectively. Moreover, the thickness of the glass film is set at 100 nm. If fabrication considerations are taken into account, including choosing a glass substrate with the appropriate thickness, the effect of the fabrication tolerances on the results is negligible.

A cavity can be considered a good candidate for achieving strong nonlinear effects. The resonance of light within the cavity increases the light intensity to higher levels at some specific frequencies. Thus, the outcome will be a strong nonlinear Kerr effect. When light with TM polarization is injected into the MIM structure, it couples to the waveguide, and SPP waves propagate along the common metal surfaces. If the wavelength of the applied light is the same as the resonant cavity wavelength, the light does not pass. This wavelength is sensitive to the dielectric constant that can be changed due to the nonlinear Kerr effect of the material. Therefore, by increasing the intensity of the input light, the wavelength changes, and switching is performed. Table 1 presents the physical and geometric parameters of the proposed switch.

### Table 1  
Physical and geometric parameters of the switch.

| Symbol | Parameter                              | Material   | Quantity   |
|--------|----------------------------------------|------------|------------|
| $n_b$  | Background refractive index             | Ag         | Drude model |
| $n_2$  | Dielectric Kerr non-linear coefficient  | Au/SiO$_2$ | 2.07 cm$^2$/GW $^{24}$ |
| $n_0$  | Dielectric linear coefficient           | Au/SiO$_2$ | 1.47$^{24}$ |
| $w$    | Waveguide width                         | Air        | 150 nm     |
| $d$    | Cavities distance                       | Ag         | 150 nm     |

The width of the waveguide and the width of the two asymmetric vertical cavities, $w$, are assumed to be 150 nm. Also, the distance between the cavities, $d$, is assumed to be 150 nm. A $100 \times 100$ nm square of gold is inserted inside the cavities.

As shown in Fig. 1(a) the structure should be placed on a glass substrate, as this will be also the case when it is studied experimentally. To ensure the feasibility of the fabrication technology, the thickness of the substrate, silver, and $\text{Au}/\text{SiO}_2$ are taken at 100, 50, and 50 nm, respectively. Moreover, the thickness of the glass film is set at 100 nm. If fabrication considerations are taken into account, including choosing a glass substrate with the appropriate thickness, the effect of the fabrication tolerances on the results is negligible.

A cavity can be considered a good candidate for achieving strong nonlinear effects. The resonance of light within the cavity increases the light intensity to higher levels at some specific frequencies. Thus, the outcome will be a strong nonlinear Kerr effect. When light with TM polarization is injected into the MIM structure, it couples to the waveguide, and SPP waves propagate along the common metal surfaces. If the wavelength of the applied light is the same as the resonant cavity wavelength, the light does not pass. This wavelength is sensitive to the dielectric constant that can be changed due to the nonlinear Kerr effect of the material. Therefore, by increasing the intensity of the input light, the wavelength changes, and switching is performed. Table 1 presents the physical and geometric parameters of the proposed switch.

### 3 Design and Simulation

The asymmetric nonlinear cavity pair of the nanostructure, shown in Fig. 1, has a strong resonant wavelength. To investigate the confined SPP modes, we calculated the transmission spectrum for the cavities. Figure 2 shows the transmission spectrum of the structure for low and high input intensities. Fig. 2 at the low intensity (0.01 mW/μm$^2$), a sharp dip occurs at the wavelength of 860 nm. This indicates that SPPs are strongly confined in the cavities without significant

![Fig. 2](image-url)  
**Fig. 2** Transmission spectrum of the proposed plasmonic switch for (a) low and (b) high input intensities.
scattering. If the input light intensity is increased to 0.1 mW/μm², the dielectric constant of the nonlinear material also increases, and the dip is red-shifted to 880 nm.

Figure 3 shows the dependency of signal transmission on the intensity of the input light at the wavelength of 860 nm. If the intensity of the input light changes, the dielectric constant changes and causes a difference in the transmission spectrum of the signal. Therefore, a mechanism is provided for the dual behavior of light at the output regarding the input light intensity. It should be noted that the constant dielectric change is due to the field intensity in the cavities. When the input light intensity is increased to 0.1 mW/μm², the signal transmission to the output increases suddenly to about 0.8. The threshold power of the signal is about 0.07 mW/μm²; therefore, only higher light intensity than the threshold power is required to realize the switching operation.

To demonstrate the performance of the incident light signal under on/off conditions, the magnetic field distribution of the structure for low and high light intensities is shown in Fig. 4. As shown, when the input light intensity is about 0.01 mW/μm², the signal is reflected,
and when the input light intensity increases to 0.1 mW/μm², it can pass the straight waveguide. The results are in good agreement with the signal transmission spectrum response under on/off conditions.

In addition to the nonlinear material with a high Kerr effect, the low light intensity required for switching is due to employing gold nanostructures inside the cavities. To ensure the validity of this issue and study the effect of these square gold nanostructures, the proposed switch structure is studied and simulated in the absence of the gold nanostructures inside the cavities. Considering the transmission spectrum of the structure in Fig. 5 for low input intensity of 0.01 mW/μm², a sharp dip in the transmission spectrum for through port is observed at a wavelength of 740 nm. The structure is scanned at this wavelength for various light intensities, and the dependency of the signal transmission to the input light intensity is shown in Fig. 6. When the light intensity is increased to 0.2 mW/μm², the transmission increases to 0.62. The threshold power of the signal is 0.15 mW/μm². The results, using square gold nanostructures reduces the input light intensity from 0.15 to 0.07 mW/μm².

To observe the effect of the asymmetry of the structure on the switch performance, the distance between the two cavities is increased from 150 to 300 nm. The structure was simulated for distances of 200, 250, and 300 nm. As the transmission spectrum in Fig. 7 shows, the asymmetry of the structure causes that an appropriate resonant frequency cannot be found for the correct operation of the switch. So, it is concluded that the structure must have symmetry.

![Fig. 5 Transmission spectrum of the proposed plasmonic switch without gold nanostructures.](image1)

![Fig. 6 Dependency of the signal transmission to the input light intensity without gold nanostructures.](image2)
It should be noted that the inherently nonlinear characteristics of gold are better than other metals, such as copper, silver, etc.

The results of the presented switch surpassed those of several other studies, indicating a significant advancement in the research. To compare the specifications of the proposed switch with other published works in recent years, the results are organized in Table 2. As shown, the proposed plasmonic switch has the highest ON-state transmission and requires the least switching power among all the structures listed in Table 2.

4 Conclusion
In this study, MIM structures, cavities, and intrinsic nonlinear properties of the gold are used to implement an all-optical plasmonic switch. The proposed switch is comprised of a bus waveguide side coupled with a pair of asymmetric vertical cavities. The dielectric in the waveguide and the two cavities are filled with air and Kerr nonlinear material, respectively. A 100 × 100 nm square of gold is also inserted inside the cavities. The transmission spectrum showed that for low input intensities, a sharp dip occurs at the wavelength of 860 nm. When the input light intensity is

![Transmission spectrum of the proposed plasmonic switch for different cavities distance: 300, 250, and 200 nm.](image)

**Table 2** Comparison of the results with previous works.

| Reference | 36 | 37 | 38 | 39 | This study (without Au) | This study (with Au) |
|-----------|----|----|----|----|------------------------|---------------------|
| Threshold power (mW/μm²) | 410 | 169 | Not reported | Not reported | 0.15 | 0.07 |
| Switching power (mW/μm²) | 650 | 217 | 193.2 | 145 | 0.2 | 0.1 |
| Wavelength (nm) | 563 | 755 | 946 | 850 | 740 | 860 |
| Transmission (ON) | 0.5 | 0.64 | 0.64 | 0.6 | 0.62 | 0.8 |
| Transmission (OFF) | 0.03 | 0.02 | 0.047 | 0.02 | 0.18 | 0.05 |
| Extinction ratio (dB) | 24.43 | 30.1 | 22.68 | 29.54 | 10.74 | 24.08 |
| Area (μm²) | 0.4 | 0.24 | 0.593 | 0.27 | 1.54 | 1.54 |
| Switching time (fs) | 100 | Not reported | Not reported | Not reported | 30 | 40 |
| Speed (Tb/s) | 10 | Not reported | Not reported | Not reported | 33 | 25 |
increased to 0.1 mW/μm², the dip of the transmission spectrum changes and the transmission power increases to 0.8. The threshold power of the structure with and without using the gold nanostructure is 0.15 and 0.07 mW/μm², respectively, showing a reduction of 50%.

References
1. V. Sasikala and K. Chitra, “All optical switching and associated technologies: a review,” J. Opt. 47, 307–317 (2018).
2. X. Zhang and J. Yang, “Ultrafast plasmonic optical switching structures and devices,” Front. Phys. 7, 190 (2019).
3. Y. Shahamat and M. Vahedi, “Designing ultra-compact high efficiency electro-optical plasmonic switches by using of nanocavity reflectors,” Opt. Commun. 410, 25–29 (2018).
4. R. Emadi et al., “Analysis and design of graphene-based surface plasmon waveguide switch at long-wavelength infrared frequencies,” IEEE J. Sel. Top. Quantum Electron. 23, 1–9 (2017).
5. M. Ghadrdan and M. A. Mansouri-Birjandi, “Implementation of all-optical switch based on nonlinear photonic crystal ring resonator with embedding metallic nanowires in the ring resonators,” Opt. Quantum Electron. 48(5), 299 (2016).
6. M. Ghadrdan and M. A. Mansouri-Birjandi, “Low-threshold photonic crystal all-optical switch using plasmonic nanowires placed in nonlinear resonator structure,” J. Nanophotonics 11(3), 036017 (2017).
7. T. Nurmohammadi, K. Abbasian, and R. Yadipour, “Ultra-fast all-optical plasmonic switching in near infrared spectrum using a Kerr nonlinear ring resonator,” Opt. Commun. 410, 142–147 (2018).
8. S. A. Maier, Plasmonics, Fundamentals and Applications, Springer (2007).
9. P. G. Kik and M. L. Brongersma, “Surface plasmon nanophotonics,” in Surface Plasmon Nanophotonics, M. L. Brongersma and P. G. Kik, Eds., pp. 1–9, Springer Netherlands, Dordrecht (2007).
10. M. A. Mansouri-Birjandi, A. Tavousi, and M. Ghadrdan, “Full-optical tunable add/drop filter based on nonlinear photonic crystal ring resonators,” Photonics Nanostruct. Fundam. Appl. 21, 44–51 (2016).
11. M. Ghadrdan and M. A. Mansouri-Birjandi, “Concurrent implementation of all-optical half-adder and AND & XOR logic gates based on nonlinear photonic crystal,” Opt. Quantum Electron. 45(10), 1027–1036 (2013).
12. K. Fasihi, “High-contrast all-optical controllable switching and routing in nonlinear photonic crystals,” J. Lightwave Technol. 32(18), 3126–3131 (2014).
13. M. K. Moazam and H. Kautzian, “Design and investigation of N-type metal/insulator/semiconductor/metal structure two-port electro-plasmonic addressed routing switch,” Appl. Opt. 54(20), 6199–6207 (2015).
14. P. P. Sahu, “Theoretical investigation of all optical switch based on compact surface plasmonic two mode interference coupler,” J. Lightwave Technol. 34(4), 1300–1305 (2016).
15. G. Song et al., “Multipath switch based on the optical bistability with surface plasmon,” Plasmonics 8(4), 1529–1534 (2013).
16. H. Liu et al., “Ultrafast and low-power all-optical switch based on asymmetry electromagnetically induced transparency in MIM waveguide containing Kerr material,” Opt. Commun. 353, 189–194 (2015).
17. B. Gökbülbül et al., “Enhanced light–matter interaction in a hybrid photonic–plasmonic cavity,” Appl. Phys. A 127, 907 (2021).
18. S.-H. Kwon, Y.-S. No, and H.-G. Park, “Design of plasmonic cavities,” Nano Convergence 1, 8 (2014).
19. Y. D. Wu, C. L. Liu, and G. Y. Jhan, “All-optical switch based on the local nonlinear plasmonic Mach-Zehnder interferometer waveguides,” in Int. Conf. Numer. Simul. of Optoelectron. Devices (NUSOD), pp. 51–52 (2015).
20. B. Janjan et al., “Ultra-wideband high-speed Mach-Zehnder switch based on hybrid plasmonic waveguides,” Appl. Opt. 56, 1717–1723 (2017).
21. R. Nanda et al., “Design of all-optical directional coupler using plasmonic MIM waveguide for switching applications,” Plasmonics 17, 2153–2159 (2022).
22. N. Nozhat and N. Granpayeh, “Switching power reduction of the plasmonic directional coupler by XPM nonlinear effect,” IEEE Photonics Technol. Lett. 24, 1154–1156 (2012).
23. S. H. Abdulnabi and M. N. Abbas, “All-optical logic gates based on nanoring insulator–metal–insulator plasmonic waveguides at optical communications band,” J. Nanophotonics 13(1), 016009 (2019).
24. N. Nozhat and N. Granpayeh, “J. Mod. Opt. 61, 1690–1695 (2014).
25. M. N. Abbas and S. H. Abdulnabi, “Plasmonic reversible logic gates,” J. Nanophotonics 14(1), 016003 (2020).
26. M. Ghadrdan and M. A. Mansouri-Birjandi, “Design and implementation of optical switches based on nonlinear plasmonic ring resonators: circular, square and octagon,” Photonics Nanostruct. Fundam. Appl. 29, 15–21 (2018).
27. A. Taflove and S. C. Hagness, *Computational Electrodynamics: The Finite-Difference Time-Domain Method* (Artech House Antennas and Propagation Library), Artech House (2005).
28. J. I. Dadap, H. B. Aguiar, and S. Roke, “Nonlinear light scattering from clusters and single particles,” *J. Chem. Phys.* **130**, 214710 (2009).
29. F. J. G. Abajo, “Nonlocal effects in the plasmons of strongly interacting nanoparticles, dimers, and waveguides,” *J. Phys. Chem. C* **112**, 17983–17987 (2008).
30. A. Taher Rahmati and N. Granpayeh, “Low power nonlinear active devices based on intrinsic metal nonlinearities,” *J. Lightwave Technol.* **32**(21), 4004–4010 (2014).
31. S. Feng et al., “Coupling between the plasmonic and photonic resonance modes in wave-guided metallic photonic crystals,” *J. Nanophotonics* **6**(1), 063513 (2012).
32. J.-T. Lin, “Nonlinear optical theory and figure of merit of surface plasmon resonance of gold nanorods,” *J. Nanophotonics* **5**(1), 051506 (2011).
33. D. K. Gramotnev and S. I. Bozhevolnyi, “Plasmonics beyond the diffraction limit,” *Nat. Photonics* **4**(2), 83–91 (2010).
34. H.B. Liao et al., “Origin of third-order optical nonlinearity in Au: SiO₂ composite films on femtosecond and picosecond time scales,” *Opt. Lett.* **23**, 388–390 (1998).
35. H. B. Liao et al., “Large third-order optical nonlinearity in Au:SiO₂ composite films near the percolation threshold,” *Appl. Phys. Lett.* **70**, 1–3 (1997).
36. H. Lu et al., “Ultrafast all-optical switching in nanoplasmonic waveguide with Kerr nonlinear resonator,” *Opt. Express* **19**, 2910–2915 (2011).
37. S. Khani, M. Danaie, and P. Rezaei, “Compact and low-power all-optical surface plasmon switches with isolated pump and data waveguides and a rectangular cavity containing nano-silver strips,” *Superlattices Microstruct.* **141**, 106481 (2020).
38. S. Khani, M. Danaie, and P. Rezaei, “Plasmonic all-optical metal–insulator–metal switches based on silver nano-rods, comprehensive theoretical analysis and design guidelines,” *J. Comput. Electron.* **20**, 442–457 (2021).
39. Y. Karimi et al., “All-optical plasmonic switches based on Fano resonance in an X-shaped resonator coupled to parallel stubs for telecommunication applications,” *Optik* **243**, 167424 (2021).

**Majid Ghadrdan** received his BS, MS, and PhD degrees in electrical engineering from the University of Sistan and Baluchestan, Zahedan, Iran, in 2010, 2012, and 2018, respectively. He then joined the University of Sistan and Baluchestan as an assistant professor. His research interests include nonlinear-optics, surface plasmon polaritons, and photonic crystals. He has served as a reviewer for a number of journals and conferences.

**Mojtaba Shahraki** received his BSc degree in electrical engineering from the University of Sistan and Baluchestan, Iran, and MSc and PhD degrees in electrical engineering from Shiraz University of Technology, Iran, in 2009, 2012, and 2017, respectively. He is now working at the University of Sistan and Baluchestan, Iran. His research interests include nonlinear optics, light management, light absorption, and nanophotonics.

**Mohammad Ali Mansouri-Birjandi** received his BS degree from the University of Sistan and Baluchestan, Iran, in 1986, MS degree from the University of Tehran, Iran, in 1991, and a PhD from Trabiat Modares University, Iran, in 2008, all in electrical engineering. He then joined the University of Sistan and Baluchestan as a professor. His research interests include photonics, optoelectronics, analog integrated circuits, and plasmonics.