Improving the performance of all-optical logic gates based on metal-insulator-metal heterogeneous plasmonic waveguide by Kerr nonlinearity effect

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Abstract
In this paper, the nonlinear effect of Kerr on increasing the efficiency of multi-channel all-optical metal-insulator-metal logic gates with heterogeneous metals is investigated. In this study, linear interference between surface plasmonic polariton modes has been employed. The performance of OR, AND, XOR and NOR gates is numerically analyzed by the finite element method. A structure with fixed physical dimensions can manage several basic logic functions. By applying optical signals to various input ports in the proposed structure, we can implement OR, AND, and XOR logic functions. The NOR logic gate can be established by the addition of a control optical signal. It has been shown that the nonlinear material of Kerr increases the difference of field intensity between logic levels of "0" and "1" that are 77 V/m for OR gate, 133 V/m for AND gate, 89 V/m for XOR gate, and 138 V/m for NOR gate. Also, simulation results show the minimum extinction ratio (ER) of 33.5, 36.4, 45.4, and 42.4 dB for OR, AND, XOR, and NOR logic gates, respectively. The proposed all-optical logic gate has a simple and compact arrangement and it can be applied to many nanophotonic components used in optical communication networks.

Keywords All-optical logic gate · Plasmonic waveguide · Kerr effect

1 Introduction
All-optical logic gates are the most significant components in optical networks (Caulfield and Dolev 2010). The fundamental concept for realizing all-optical basic logic gates is to use the magneto-optic effect, the electro-optic effect, and the linear interference of light propagating. So, they have been designed based on many different structures such as all-optical logic gates based on semiconductor optical amplifiers (SOAs) (Kotb et al. 2016;
periodically poled lithium niobate (PPLN) (Wang et al. 2007, 2008) waveguides, highly nonlinear fiber (HNLF) (Li et al. 2010; Jasim et al. 2019), photonic crystals (PhC) (Rani et al. 2017; Rao et al. 2021), plasmonic waveguides (Sharma et al. 2018; Pal et al. 2021; Anguluri et al. 2021), and so on. Typically, the structure of all-optical gates based on SOA consists of an optical fiber with nonlinear properties and a semiconductor optical amplifier integrated with other necessary optical components. The extinction ratio value of more than 50 dB for NOT & XOR triple all-optical gates based on dual SOA has been reported (Raja et al. 2021). In this structure, it's used the effect of nonlinear cross-polarization modulation. In another work, a high-quality factor for all-optical gates using four-wave mixing in broadband SOA has been achieved (Hejib et al. 2021). Also, an optimal state with minimal energy for pulse input at a high-speed all-optical NAND logic gate using a photonic crystal-semiconductor optical amplifier (PC-SOA) has been reported (Heydarian et al. 2022). This gate is based on a Mach Zander interferometer and nonlinear cross-phase modulation mechanism. All-optical gates based on SOA are suitable for practical usage because of their compactness and integration with other optical components such as array structures, waveguides, and filters. However, semiconductor optical amplifiers (SOA) have limitations such as gain saturation and low switching speed due to the long carrier lifetime (Kotb et al. 2021). In addition, logic gates implemented by using cross-interest modulation (XGM) and cross-phase modulation (XPM) in SOA consume high power to achieve nonlinear effects.

Periodically poled lithium niobate (PPLN) is a highly efficient medium for nonlinear wavelength conversion processes. PPLN is used for frequency doubling, difference frequency generation, sum-frequency generation, optical parametric oscillation, and other nonlinear processes. By using the PPLN waveguide, high-speed logic operations such as half-adder, half subtractor, and AND/OR/XOR gates have been achieved (Bogoni et al. 2009). For these gates, it's exploited the combination of sum- and difference-frequency generation (SFG-DFG) and pump depletion processes. Complete transparency, no excess noise, and ultra-fast response (about 40 Gbit/s for OR logic gate based on the cascaded SFG-DFG (Wang et al. 2007)) are attractive properties of PPLN (Wang et al. 2008). However, diffraction limitations in PPLN-based devices and the large size of lithium-niobate crystals of a few millimeters, limit the application of these devices in the integrated circuits (Chattopadhyay 2013; Yang et al. 2017).

Highly nonlinear fibers (HLNF) are usually passive optical fibers that are designed such that they exhibit relatively strong optical nonlinearities. By using HLNF, an FWM-based all-optical logic gate that simultaneously implements XOR, AB, AB, OR, XNOR, AND, and NOR logic gates have been reported (Li et al. 2010). By this structure, 10Gbps speed and a minimum quality factor of 8 dB have been achieved. Also, in the paper of (Jasim et al. 2019), an architecture was proposed by third-order Kerr nonlinear effect on HLNF. In this research, the Self-phase and cross-phase modulation phenomena have been applied for a reconfigurable photonic XOR logic gate. The HNLF-based logic gates can achieve enhanced power efficiency and higher data rates with a relatively high nonlinear coefficient. The HNLF performs the same logical operations as SOA as a passive device and has low optical power levels (Jasim et al. 2019). Although, the widespread integration of HNLF-based logic gates at the chip level creates a limitation due to their physical size (Shaik et al. 2016; Singh et al. 2021).

On the other hand, one of the challenges in designing optical logic gates is the issue of light interference, which is due to the wavy property of light. The logic gates based on linear optical interference usually have a small difference in intensity between the two logic levels of "0" and "1" (Li et al. 2005; Zhang et al. 2007). The logic operations depend on the
optical phase ratio of the two input signals, but accurate control of optical phase difference is not easy and the creation of constructive or destructive interferential modes of signals is almost difficult (Sankar and Philip 2018). This problem can be solved by downsizing the device such as photonic crystal structures (Fu et al. 2013). However, compact interfering logic gates based on these structures cannot have physical dimensions in the subwavelength scale due to diffraction limitations.

To achieve a satisfactory relation between the loss and optical confinement, different geometries of plasmonic waveguides have been reported. Superficial plasmon structures can limit or transmit light in the subwavelength range (Onuki et al. 2003; Moradipour et al. 2021). Metal-insulator-metal (MIM) waveguide has been extensively used for designing and developing logic functions because of its capability of confining the charge carriers at a deep subwavelength scale. So far, many examples of such plasmonic interfering structures based on metal nanowire networks and metal slot waveguides have been investigated (Lu 2013; Pan 2013; Papaioannou 2016). However, to implement all basic logic functions, different structures are needed, which makes the design and application of these components complex.

To solve this limitation, a suitable all-optical logic device based on plasmonic waveguides has been presented (Bian and Gong 2014). By using numerical simulation of the proposed structure at wavelength 1550 nm, the basic logic gates, OR, AND, NOT, XOR, XNOR, NAND, and NOR have been implemented, without any modification or reconfiguration of the device. In this design, a general logic device is constructed using a metal-insulator-metal waveguide (MIM).

In this paper, to increase the level difference between the logic states of "0" and "1", heterogeneous metals of gold, aluminum, and silver, as well as Kerr nonlinear material, have been used. The proposed gate structures have a simple structure, nanoscale light confinement, minimal interference, acceptable propagation distance, and very high transmission. The logic gates based on metal-insulator-metal (MIM) can create logic functions by displacing optical signals through input and control channels. Also, we show a high difference level between the logic levels of "0" and "1". The innovation of this design is that a unique structure can be implemented for all logic gates. It uses several different types of metals and their surface plasmonic properties, as well as Kerr nonlinear material to improve the performance of all-optical logic gates. It also can integrate plasmonic logic gates in the chip with photonic integrated circuits.

2 Design of all-optical logic gate based on the metal-insulator-metal structure

Considering that our main goal is to achieve all-optical logic gates with a high extinction ratio (ER) using nonlinear effects of light in the components of the structure, we investigated different designs that increase the nonlinear effects of light and thus improve the performance of logic gates. One of the nonlinear effects of light that leads to changes in phase matching operations is the effect of the second harmonic output. To increase the second harmonic conversion factor, it is necessary to combine the even and odd plasmonic modes inside the waveguide. One of the methods of manipulating plasmonic modes is an asymmetry in the metal surrounding the waveguides. Therefore, in our initial research, we examined several structures that increase the nonlinear effects and thus improve the performance of the desired gates. In the structure number 1, all metals are made of silver (Fig. 1a). In the
structure number 2, the gate with gold and silver metals is examined (Fig. 1b). In the structure number 3, three different metals; gold, silver, and aluminum are simulated (Fig. 1c). In the structure number 4, in addition to using three different metals, in the channel between paths 1, 2, 3, and 4, instead of using air inside the waveguides, we used a nonlinear material (Fig. 1d). This theme is chosen according to Kerr’s nonlinearity effect. Due to the Kerr nonlinear material, the refractive index of the selected nonlinear material changes with the change in field intensity. It should be noted that nonlinear optical effects occur in relatively strong fields and plasmonic structures can meet the condition of high field intensity due to the strong field concentration within the waveguides. In the present paper, our focus is on the structure number 3 (with heterogeneous metals) and the structure number 4 (considering the Kerr nonlinearity effect). So, we did not discuss the results of the other structures. But, a comparison of the extinction ratio (ER) in the total four proposed logic gates with the other reported works is presented in end of the article.

The two-dimensional structure of the first proposed design (structure number 3) is shown in Fig. 2a. This structure consists of four air channels located on the substrate of silver, gold, and aluminum as input ports and one output channel. The input signals are directed through ports I₁, I₂, and I₃. Port C is also required as a control port for the creation of certain logic functions. The same thickness (d) is considered for all channels. The distance between all channels is constant and equal to L. To understand the concept of
device performance, in the simulations of logic gates, 90° sharp corners are considered for all air channels. Certainly, by implementing bends with larger angles and rounded corners, the output characteristics of the devices are improved. These include lower propagation losses, higher extinction ratios (ER), and thus higher device efficiency. The permittivity of air, silver, gold, and aluminum are considered \( \varepsilon_{\text{air}} = 1 \), \( \varepsilon_{\text{Ag}} = -129 + 3.3i \), \( \varepsilon_{\text{Au}} = -113.53 + 9.268i \), and \( \varepsilon_{\text{Al}} = -197.92 + 38.85i \), respectively.

The results show that the real part of the modal effective index and the propagation losses of plasmonic modes decreases with an increase in channel thickness. But the size of the corresponding mode increases (Bian and Gong 2014). We investigated the surface plasmon mode traveling along air channels cut into Ag, Ag/Au and Ag/Au/Al backgrounds. Figures 3 and 4 indicate the real part of the modal effective index (\( \text{Re}(N_{\text{eff}}) \)) and the propagation length of the plasmonic mode (\( L = \lambda/[4\pi \text{Im}(N_{\text{eff}})] \)) as a function of the thickness of the air channel (\( d \)), respectively.

As shown, in Ag/Au/Al background for air channel thickness greater than 50 nm, the real part of the effective index remains constant. So, we considered 50 nm to 100 nm thickness for air channel to establish single-mode conditions, acceptable propagation losses as well as minimum physical dimension. The choice of this range is due to the real part of the effective index remains constant in the considered thickness of the channels.

![Geometry of proposed structures for all-optical logic gate using different metals](image)

Fig. 2 Geometry of proposed structures for all-optical logic gate using a three different metals, b three different metals and Kerr nonlinear material

![The real part of modal effective index versus the thickness of air channel](image)

Fig. 3 The real part of modal effective index versus the thickness of air channel
Also, to reduce the coupling between the input signals of the channels, the distance between all the channels must be larger than the critical required value to ensure the correct logic operations without significant crosstalk between different channels (Bian and Gong 2014). We calculated the dependence of normalized coupling length on the distance between two MIM waveguides (L) in the proposed optical gates for three structures with Ag, Ag/Au and Ag/Au/Al backgrounds (Fig. 5). As shown, it was obtained the critical distance between adjacent channels equals 200 nm for Ag/Au/Al background (the normalized coupling length can be bigger than 1). So, to reduce the coupling between the input signals as well as the required constructive and destructive interferences, we considered the optimal distance between the channels equal to 550 nm.

The two-dimensional geometry of the second proposed structure (structure number 4) is shown in Fig. 2b. This structure is the same as the first one. Only at the outlet of channels I₁ and I₂ and their connection to channels I₃ and C, a Kerr nonlinear material with a nonlinear coefficient of $1 \times 10^{16}$, and linear dielectric constant of 2.31 is used instead of air inside the waveguide (highlighted in red in Fig. 2b). The optical specifications of logic gates based on metal-insulator-metal have been studied at 1550 nm by the finite element method (FEM). The FEM breaks the surface into small sections and solves electromagnetic equations for complete structure by meshing cells per wavelength. At first, the modal properties of the MIM waveguide are analyzed by solving the eigenmode equations, and then to
perform a full-wave 2D numerical simulation of the mode propagation along the channels. The 2D field distribution in the MIM heterogeneous plasmonic waveguide is obtained by solving eigenmode equations. The perfectly matched layer (PML) absorbing boundary conditions and meshing of 20 cells per wavelength are considered.

### 3 Results and discussion

The operation of optical logic gates is considered to be based on the wavy property of light. If the phase difference between two light beams is $2k\pi$, constructive interference will take place between the two beams, and creates a relatively high-intensity output signal. However, if the phase difference between two light beams is $(2k + 1)\pi$, destructive interference takes place and as a result, the output signal is obtained with an intensity of almost zero (Sankar and Philip 2018). With a correct definition of threshold intensity, the high and low logic levels can be obtained based on both constructive and destructive interference (Bian and Gong 2014). According to the proposed structure, the difference in the optical paths for different channels causes constructive or destructive interference for the input optical signals. There is no difference in the optical path between the signals on channels $I_1$ and $I_2$, which leads to a zero-phase difference. While there is an optical path difference for channels $I_1$ (or $I_2$) and $I_3$ (or $C$) which is equal to half of the effective wavelength of the guided plasmonic modes (Bian and Gong 2014), a phase difference is brought about in $\pi$. Therefore, we have constructive interference for the signals of channels $I_1$ and $I_2$, while the signal in channels $I_3$ and $C$ creates a destructive interference with channels $I_1$ and $I_2$ in the output.

To realize different logic operations, there is a need for the combination of two or more channels in the logic gate. Table 1 shows the combinations of entering signals to different channels for the OR, AND, XOR, and NOR logic gates. Implementation of OR, AND, and XOR logic gates can be activated by combining the two input channels. By applying the constructive interference between the $I_1$ and $I_2$ signals and correctly defining the threshold intensity, OR and AND logic gates can be accomplished. Also, by applying the destructive interference between the $I_2$ and $I_3$ signals, the XOR gate can be performed. On the other hand, to accomplish the NOR logic function, the signal in the control channel must also be activated. For the NOR gate, both the channel signals of $I_1$ and $I_2$ must be combined with the $C$ control signal. In the NOR gate, the intensity of the control signal must be twice as great as the input signals. The NOR gate can be performed by correct determination of the threshold intensity.

### Table 1

| Gate | Input channel $I_1$ | Input channel $I_2$ | Input channel $I_3$ | Input channel $C$ |
|------|--------------------|--------------------|--------------------|------------------|
| OR   | Enabled            | Enabled            |                    |                  |
| AND  | Enabled            | Enabled            |                    |                  |
| XOR  | Enabled            | Enabled            | Enabled            |                  |
| NOR  | Enabled            | Enabled            |                    | Enabled          |
The performance of the OR gate operation is shown in Table 2. By applying an optical signal to the input ports of channels I1 and I2 and without any requirement to activate the control signal, the output logic levels can be changed from "0" to "1". Figure 6 shows the distribution of the magnetic field for various logic states.

Table 2 The procedure of using gate channels to implement the OR logic gate

| Gate | Input channel I1 | Input channel I2 | Input channel I3 | Input channel C | Output channel |
|------|------------------|------------------|------------------|-----------------|----------------|
| OR   | "0"              | "0"              | Disable          | "0"             | "0"            |
|      | "0"              | "1"              | Disable          | "1"             | "1"            |
|      | "1"              | "0"              | Disable          | "1"             | "1"            |
|      | "1"              | "1"              | Disable          | "1"             | "1"            |

Fig. 6 The Magnetic field distributions (|H x|) for different states of OR logic gate: a “0 OR 1 = 1” b “1 OR 0 = 1” and c “1 OR 1 = 1”

3.1 The OR gate performance

The performance of the OR gate operation is shown in Table 2. By applying an optical signal to the input ports of channels I1 and I2 and without any requirement to activate the control signal, the output logic levels can be changed from "0" to "1". Figure 6 shows the distribution of the magnetic field for various logic states.

According to Fig. 6a, b, if a signal enters the I1 or I2 channels, this optical signal can be transmitted through the associated channel and appears at the output port corresponding to the logic operation "1 OR 0 = 1" or "0 OR 1 = 1". On the other hand, if the signal is injected simultaneously into both the input ports of channels I1 and I2 (Fig. 6c), the optical signal can be transmitted through both channels and reach the output channel in a combined form. This is because channels I1 and I2 have a similar light path, therefore making
the phase difference of the two optical beams zero. Then, constructive interference is established between them, resulting in high optical signal intensity at the output port. As a result of this process, the logic operation "1 OR 1 = 1" can be accomplished.

The output field intensity diagram of the logic level "1" for the first and second proposed structures of the OR logic gate is shown in Fig. 7. By comparing the results, it is clear that with the Kerr nonlinear material, the field intensity has increased by 77 V/m, i.e. about 22%, when the second structure is compared to the first one. The reason for this can be attributed to that in the logic operation "1 OR 1 = 1", due to the constructive interference between the two channels $I_1$ and $I_2$, the field intensity at the part of the nonlinear material increases. It leads to a change in the refractive index of this location and based on the nonlinear effect, more intense phase matching and stronger coupling occur.

Two important parameters of the logic gates’ performance are extinction ratio (ER) and modulation defined as follows:

$$ER = 10 \log_{10} \left( \frac{P_{out}(1)}{P_{out}(0)} \right)$$

where $P_{out}(1)$ is the output optical power in the high state and $P_{out}(0)$ is the output optical power in the low state. MD can be calculated as follows:

$$MD = \frac{T_{on} - T_{off}}{T_{on}}$$

where $T_{on}$ and $T_{off}$ are the transmissions in the ON and OFF states, respectively. The output power, the minimum extinction ratio, and the modulation depth for the OR gate are presented in Table 3. As depicted, the minimum extinction ratio for the first and second proposed structures is 30.2 dB and 33.5 dB, respectively. Also, modulation depth for the first and second proposed structures is 99.90% and 99.95%, respectively.

### 3.2 The AND gate performance

To investigate the performance of the AND logic gate, a structure similar to that used for the OR logic gate can be employed. The AND logic operation can be accomplished by the correct definition of the threshold intensity. Table 4 shows the operation of the AND gate.
| A | B | OR output | $P_{\text{out}}$ (1st Str.) (dB) | $P_{\text{out}}$ (2d Str.) (dB) | Min ER (1st Str.) | Min ER (2d Str.) | MD (1st Str.) | MD (2d Str.) |
|---|---|-----------|-------------------------------|-------------------------------|----------------|----------------|-------------|-------------|
| 0 | 0 | 0         | −35.7                         | −38.3                         | 30.2 dB        | 33.5 dB        | 99.90%     | 99.95%      |
| 0 | 1 | 1         | −5.3                          | −4.8                          | 30.2 dB        | 33.5 dB        | 99.90%     | 99.95%      |
| 1 | 0 | 1         | −5.5                          | −4.7                          | 30.2 dB        | 33.5 dB        | 99.90%     | 99.95%      |
| 1 | 1 | 1         | −4.1                          | −3.7                          | 30.2 dB        | 33.5 dB        | 99.90%     | 99.95%      |
and its associated settings. According to the table, the logic level "1" appears in the output port only when the input port of both channels has an optical signal.

The distribution of magnetic fields in various logic states is shown in Fig. 8. As shown in Fig. 8a, b, if an optical signal is applied to channel I₁ or channel I₂, the optical signal can be transmitted through one of the two channels and reaches the output port.

Figure 8c shows that if the optical signal is applied simultaneously to the input port of channels I₁ and I₂, the optical signal can reach the output channel in combination. By setting a proper intensity threshold between the above two cases, the logic states of "0" and "1" can be accomplished, respectively. According to appropriate definitions, the first two processes are related to the logic function of "1 AND 0 = 0" and "0 AND 1 = 0", while the third process confirms that the logic function of "1 AND 1 = 1". The diagram of the output

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**Table 4** The gate channel procedure to implement the AND logic function

| Gate | Input channel I₁ | Input channel I₂ | Input channel I₃ | Input channel C | Output channel |
|------|------------------|------------------|------------------|-----------------|---------------|
| AND  | "0"              | "0"              | Disable          | "0"             |
|      | "0"              | "1"              | Disable          | "0"             |
|      | "1"              | "0"              | Disable          | "0"             |
|      | "1"              | "1"              | Disable          | "1"             |

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**Fig. 8** The Magnetic field distributions (|Hₓ|) for different states of AND logic gate: a "0 AND 1 = 0", b "1 AND 0 = 0" and c "1 AND 1 = 1"
field intensity difference between the logic levels of "0" and "1" for the first and second proposed structures of the AND logic gate is shown in Fig. 9.

It can be seen that the difference in output field intensity for the state of "0 AND 1 = 0" and the state of "1 AND 1 = 1" in the first structure is 184 V/m (the distance between continuous blue and red lines), while the difference in the second structure has reached 317 V/m (the distance between the blue and red dashes).

By comparing the above results, it is clear that the difference between the logic levels in the second structure, despite the Kerr nonlinear material, has increased by about 133 V/m relative to the first structure, i.e. 72%. It can also be seen that in the second structure, the state of "1 AND 1 = 1" increases, and the state of "0 AND 1 = 0" decreases. The reason for this can be attributed to the fact that in the logic operation "0 And 1 = 0", the on-state signal of channel I1 or I2 alone cannot greatly increase the field intensity and take little advantage of the Kerr nonlinear effect. While in the logic operation "1 And 1 = 1", the simultaneous presence of the signal in the two-channel I1 and I2, the intensity of the field passing through the part of Kerr nonlinear material increases and causes that more intense phase matching and stronger coupling occur.

The output power, the minimum extinction ratio, and the modulation depth for the AND gate are presented in Table 5. As depicted, the minimum extinction ratio for the first and second proposed structures is 28.9 dB and 36.4 dB, respectively. Also, modulation depth for the first and second proposed structures is 99.87% and 99.97%, respectively.

### 3.3 The XOR gate performance

For the implementation of the XOR logic operation, we need the destructive interference between optical signals of I2 and I3 channels. The operating principles of the XOR gate have been shown in Table 6. The magnetic field distribution for the various logic states has been shown in Fig. 10.

As shown in Fig. 10a, b, if a signal enters the input channel I2 or I3, the light beam can be transmitted through the connected channel and placed at the output port corresponding to the logic operations of "1 XOR 0 = 1" or "0 XOR 1 = 1". On the other hand, if a signal is applied simultaneously to both input ports of channels I2 and I3 (Fig. 10c), the signal is transmitted and reaches the output channel in a combined form. According to what is mentioned in (Bian and Gong 2014), the difference in the optical path
### Table 5  The output power, the minimum ER, and MD for the AND logic gate

| A | B | AND output | Pout (1st Str.) (dB) | Pout (2d Str.) (dB) | Min ER (1st Str.) | Min ER (2d Str.) | MD (1st Str.) | MD (2d Str.) |
|---|---|------------|----------------------|---------------------|------------------|------------------|--------------|--------------|
| 0 | 0 | 0          | −36.3                | −41.7               | 28.9 dB          | 36.4 dB          | 99.87%       | 99.97%       |
| 0 | 1 | 0          | −33.2                | −40.1               |                  |                  |              |              |
| 1 | 0 | 0          | −33.1                | −40.3               |                  |                  |              |              |
| 1 | 1 | 1          | −4.2                 | −3.7                |                  |                  |              |              |
between channels $I_2$ and $I_3$ is $\lambda_{\text{eff}}/2$, which is related to the phase difference $\pi$. In this case, the destructive interference between the optical signals in channels $I_2$ and $I_3$ brings about an output with almost zero intensity at the output port, which is related to the logical operation of "$1 \text{ XOR } 1 = 0$".

Figure 11 shows the result of comparing the performance of the XOR gate of the first and second structures. The difference between the logic levels of "$0$" and "$1$" in the output of this gate has reached $131$ V/m for the first structure and $220$ V/m for the second structure. That is, the second structure compared to the first structure was able to increase $89$ V/m, i.e. $67\%$. It can be seen that the bright states have been shown a noticeable difference. Since the final state in XOR (in this diagram) results from the

| Gate | Input channel I1 | Input channel I2 | Input channel I3 | Input channel C | Output channel |
|------|------------------|------------------|------------------|-----------------|----------------|
| XOR  | "0"              | "0"              | Disable          | "0"             |                |
|      | "0"              | "1"              | Disable          | "1"             |                |
|      | "1"              | "0"              | Disable          | "1"             |                |
|      | "1"              | "1"              | Disable          | "0"             |                |

Fig. 10 The Magnetic field distributions (|Hx|) for different states of XOR logic gate: a "$0 \text{ XOR } 1 = 1$", b "$1 \text{ XOR } 0 = 1$" and c "$1 \text{ XOR } 1 = 0$"
reaching of the I₃ channel signal to the output, it is then clear that the nonlinear effects occurred most strongly in the asymmetric waveguide of the I₃ channel surrounded by gold and aluminum. It can be concluded from these results that by using Kerr nonlinear effect, the second structure has led to an increase in the difference in logical levels relative to the first structure.

The output power, the minimum extinction ratio, and the modulation depth for the XOR gate are presented in Table 7. As depicted, the minimum extinction ratio for the first and second proposed structures is 35.4 dB and 45.3 dB, respectively. Also, modulation depth for the first and second proposed structures is 99.97% and 99.99%, respectively.

3.4 The NOR gate performance

To design the NOR gate, we need a double signal intensity in the C control channel. The logical operation of the NOR gate can be accomplished by correctly defining the threshold intensity. Table 8 indicates the operating principles of the NOR gate. The distribution of magnetic fields for different logic levels is shown in Fig. 12.

Figure 12a illustrates the logic operation of "0 NOR 0 = 1", while Fig. 12b, c, d is related to the logic operations of "1 NOR 0 = 0", "0 NOR 1 = 0", and "1 NOR 1 = 0", respectively.

According to Fig. 12a, when no signal is applied to the inputs, the control signal is placed at the output through the C channel. So, when no signal is applied to the input, the output will be at level "1". On the other hand, if a signal is applied to the input ports of channels I₁ or I₂ (Fig. 12b, c), the light is transmitted through these channels, and after combining with the control signal, it reaches the output channel. In this case, there is destructive interference between the signals of channels I₁ or I₂ with the control channel, and because the intensity of the control signal is twice of the input signals, the signal intensity at the output is less than that of control signal intensity, and of course more than zero.

Figure 12d shows the state in which the signal is applied simultaneously to the input ports of channels I₁ and I₂. Due to the complete destructive interference between the control channel and channels I₁ and I₂, a light with almost zero intensities appears at the output of the gate.

The employment of the second proposed structure in the NOR gate, also significantly increases the difference between the logic levels of "0" and "1". This is observable from the field intensity diagram of the output port in Fig. 13. The second proposed structure has been able to increase the difference between the logic levels by 138 V/m, i.e. 44%,
Table 7: The output power, the minimum ER, and MD for the XOR logic gate

| A | B | XOR output | Pout (1st Str.) (dB) | Pout (2nd Str.) (dB) | Min ER (1st Str.) | Min ER (2nd Str.) | MD (1st Str.) | MD (2nd Str.) | %               |
|---|---|------------|---------------------|---------------------|-------------------|-------------------|---------------|---------------|-----------------|
| 0 | 0 | 0          | −43.2               | −52.7               | 35.4 dB           | 45.3 dB           | 99.97%        | 99.99%        | 99.99%          |
| 0 | 1 | 1          | −7.8                | −6.5                | −7.5              | −6.2              |               |               |                 |
| 1 | 0 | 1          | −7.5                | −6.2                | −7.5              | −6.2              |               |               |                 |
| 1 | 1 | 0          | −43.4               | −51.8               | −43.4             | −51.8             |               |               |                 |
compared to the first structure. The reason for this increase in the field intensity of logic operations of "0 NOR 0 = 1" (red dashed line) is related to the control channel. In this case, the output signal is supplied through the control channel; the gold below this waveguide and the aluminum on top of it increase the nonlinear effects by combining different plasmonic modes in such an asymmetric waveguide. As mentioned, in the NOR logic gate, channels $I_1$ and $I_2$ are used as inputs and channel $C$ is used for control. The on-state of this gate is "0 NOR 0 = 1" due to channel $C$, which reaches the output without colliding with the nonlinear material at the junction of the channels. Because the field intensity in this channel is not enough to pass nonlinear material, it reaches the output without losses and enters other parts.

The output power, the minimum extinction ratio, and the modulation depth for the NOR gate are presented in Table 9. As depicted, the minimum extinction ratio for the first and
The second proposed structures is 38 dB and 42.2 dB, respectively. Also, modulation depth for the first and second proposed structures is 99.98% and 99.99%, respectively.

The comparison of the extinction ratio in the proposed logic gates with the other reported works is shown in Table 10. As shown, the proposed work is better than others in terms of ER.

4 Fabrication techniques

The deposition of plasmonic metals can be done in a vacuum using sputtering or evaporation techniques. To obtain satisfactory uniformity, the deposition rate is generally limited to less than 1 nm/s. The low deposition rate is not an important concern because the required plasmonics structure height for optical gates is small (Kazanskiy et al. 2020). There are limited effective methods available to etch Ag, Au and Al. Two common methods are widely used for pattern metals. The first method is through the image reversal and lift-off process, which requires special photoresists (such as lift-off resist (LOR)) for the lift-off process. A second method to pattern metal is through ion milling. A focused ion beam can be used to directly mill patterns into Ag and Au films (Kannegulla et al. 2016). The argon ion beam (Hindmarch et al 2012) is an alternative to etch noble metals but it needs hard masks and may increase the fabrication steps and the processing complexity. So, after the metal layers are deposited using e-beam evaporation on a substrate (such as silicon or quartz), the slits as air channels are fabricated into the metal layers using e-beam lithography with positive (or negative) photoresist, or through focused-ion-beam (FIB) milling.

5 Conclusion

By investigating the simulation results of the proposed structures through the method of finite elements, it has been shown that by using heterogeneous metals and Kerr nonlinear material the all-optical logic gate improves its performance and increases the level difference between the logic levels. In this paper, OR, AND, XOR, and NOR logic gates were implemented. It has been shown that the linear interference between the surface plasmonic polariton modes makes the desired output of the logic gate. The advantage of the proposed
| A  | B | NOR output | \( P_{out} \) \(1\text{st Str. (dB)}\) | \( P_{out} \) \(2\text{d Str. (dB)}\) | \( \text{Min ER (1st Str.)} \) | \( \text{Min ER (2d Str.)} \) | \( \text{MD (1st Str.)} \) | \( \text{MD (2d Str.)} \) |
|----|---|------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 0  | 0 | 1          | −6.7           | −6.1           | 38 dB          | 42.2 dB        | 99.98%         | 99.99%         |
| 0  | 1 | 0          | −44.7          | −48.3          |                |                |                |                |
| 1  | 0 | 0          | −44.9          | −49.2          |                |                |                |                |
| 1  | 1 | 0          | −50.2          | −55.6          |                |                |                |                |

Table 9 The output power, the minimum ER, and MD for the NOR logic gate.
| Gate structure                                      | Structure/material used                                    | Gate logic | Extinction ratio (dB) | Wavelength (µm) | References                  |
|-----------------------------------------------------|----------------------------------------------------------|------------|-----------------------|-----------------|-----------------------------|
| The triangular lattice of air holes in silicon      | 2D photonic crystals                                      | NOT        | 5.42                  | 1.55            | Rani et al. (2015)          |
|                                                     |                                                          | AND        | 8.76                  |                 |                             |
|                                                     |                                                          | OR         | 8.21                  |                 |                             |
|                                                     |                                                          | XOR        | 8.49                  |                 |                             |
|                                                     |                                                          | XNOR       | 5.42                  |                 |                             |
|                                                     |                                                          | NOR        | 5.42                  |                 |                             |
|                                                     |                                                          | NAND       | 9.59                  |                 |                             |
| Array of air rods in silicon                        | 2D photonic crystals                                      | NOT        | 3.74                  | 1.55            | Rani et al. (2017)          |
|                                                     |                                                          | AND        | 11.47                 |                 |                             |
|                                                     |                                                          | OR         | 12.48                 |                 |                             |
|                                                     |                                                          | XOR        | 6.5                   |                 |                             |
|                                                     |                                                          | XNOR       | 6.5                   |                 |                             |
| 21 × 21 array of Si rods                            | 2D photonic crystals                                      | AND        | 33.05                 | 1.55            | Rao et al. (2021)           |
|                                                     |                                                          | OR         | 10.5                  |                 |                             |
|                                                     |                                                          | XOR        | 8.29                  |                 |                             |
| Y-combiner                                          | Hybrid metal insulator metal plasmonic waveguide (Ag-SiO2-Si) | XOR        | 26                    | 1.55            | Sharma et al. (2018)        |
|                                                     |                                                          | NOT        | 26                    |                 |                             |
| Two S-bends MIM waveguides                         | Plasmonic waveguide                                      | XOR        | 27.8                  | 1.55            | Pal et al. (2021)           |
| Y-combiner                                          | Plasmonic MIM waveguide                                  | AND        | 14.11                 | 1.55            | Angular et al. (2021)       |
| Multilayer graphene waveguide structure             | Graphene Plasmons                                        | OR         | 13.6                  | 9.5             | Zhu et al. (2016)           |
|                                                     |                                                          | NOR        | 17.5                  |                 |                             |
|                                                     |                                                          | AND        | 17.5                  |                 |                             |
|                                                     |                                                          | NAND       | 13.6                  |                 |                             |
| QD-SOA                                              | Mach Zehnder                                             | XOR        | 20                    | 1.3             | Han et al. (2008)           |
| MQW-SOA                                             | Double micro ring resonator                              | XNOR       | 17                    | 1.55            | Akashi et al. (2018)        |
| PPLN                                                | Cascaded Mach–Zehnder modulators and tunable laser        | AND        | 20                    | ~ 1.55          | Wang et al. (2008)          |
| Gate structure                        | Structure/material used                 | Gate logic | Extinction ratio (dB) | Wavelength (µm) | References                  |
|--------------------------------------|----------------------------------------|------------|-----------------------|-----------------|----------------------------|
| HNLF                                 | Highly nonlinear fiber                 | XOR        | 11.217                | 1.55            | Jasim et al. (2019)        |
| Y-combiner                           | Graphene/dielectric/Au layers          | AND        | 29.41                 | 10.96           | Rezaei et al. (2018)       |
|                                      |                                        | NOR        | 29.40                 |                 |                            |
| MIM-plasmonic waveguide              | Silver                                 | OR         | 22.1                  | 1.55            | This Work                  |
|                                      |                                        | AND        | 23.8                  |                 |                            |
|                                      |                                        | XOR        | 24.2                  |                 |                            |
|                                      |                                        | NOR        | 24                    |                 |                            |
| MIM-heterogeneous plasmonic waveguide| Silver, gold                           | OR         | 28.2                  | 1.55            | This Work                  |
|                                      |                                        | AND        | 27                    |                 |                            |
|                                      |                                        | XOR        | 33.3                  |                 |                            |
|                                      |                                        | NOR        | 32.8                  |                 |                            |
| MIM-heterogeneous plasmonic waveguide| Silver, gold, and aluminum             | OR         | 30.2                  | 1.55            | This Work                  |
|                                      |                                        | AND        | 28.9                  |                 |                            |
|                                      |                                        | XOR        | 35.4                  |                 |                            |
|                                      |                                        | NOR        | 38                    |                 |                            |
| MIM-heterogeneous plasmonic waveguide| Silver, gold, and aluminum by Kerr Nonlinearity Effect | OR        | 33.5                  | 1.55            | This Work                  |
|                                      |                                        | AND        | 36.4                  |                 |                            |
|                                      |                                        | XOR        | 45.3                  |                 |                            |
|                                      |                                        | NOR        | 42.2                  |                 |                            |
structure is that a structure with fixed physical dimensions can accomplish several basic logic functions. It has been shown that the nonlinear material of Kerr increases the difference in logic levels of "0" and "1" for OR gate by 23%, for AND gate by 72%, for XOR gate by 67%, and NOR gate by 44%. The results show the minimum extinction ratio of 33.5 for OR, 36.4 for AND, 45.4 for XOR, and 42.4 dB for NOR logic gates. The simple and compact arrangement of all-optical logic gates based on heterogeneous metal-insulator-metal plasmonic waveguides can be used in many nanophotonic devices. For practical applications and fabrication of proposed logic gates, several important issues should be considered, including the properties of the excitation laser beam, losses due to fabrication process imperfections of the gate, signal-to-noise ratio, and bandwidth. Also, by choosing a shorter operation wavelength, the overall size of the gate structure can be designed smaller.

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