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Highly Directive Hybrid Plasmonic Leaky Wave Optical Nano-Antenna

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Abstract—A novel traveling-wave hybrid plasmonic optical antenna is proposed for operation at the standard telecommunication wavelength of 1550 nm and with the frequency bandwidth of more than 16 THz. A highly directive radiation pattern with 15.2 dBi directivity and 82% efficiency is achieved. The developed antenna benefits from high directivity advantage of leaky-wave antennas, and low loss properties and confinement of hybrid plasmonic structures. The designed device can have applications in inter/intera chip optical interconnect, and absorption enhancement of photodetectors, and solar cells.

1. INTRODUCTION

Introduction of the antenna concept into the optical near infrared and terahertz frequency regime holds promise for a wide range of novel applications [1–16] including photo-detection [2, 3], sensing [4], heat transfer [5, 6], and spectroscopy [16].

Although designing microwave antennas has a rich literature, developing optical antennas has just started recently due to their challenging fabrication which requires nano-technology [11, 13]. Due to the very different behavior of metals at optical frequencies, with respect to the behavior of their counterpart at radio-band and microwave frequencies, a nano-antenna operating at optical frequencies is not a simple downscaled version of a microwave antenna. Therefore, recently different research groups around the world have been working to develop new methods to analyze [7, 8], synthesize [9, 10], and feed optical antennas [12] employing surface plasmon theory and rich antenna theory.

In most of the previous researches on nano-antennas, these devices have been designed to either confine the light coming from free-space [14] or redirect the light coming from a point source [15], for applications such as spectroscopy [16] and sensing [4]. However, for the optical communication applications, the antenna must be designed in such a way to be compatible and therefore be fed by an integrated waveguide. This kind of antenna would be able to receive an optical signal from an Integrated Photonic Circuit (IPC) and radiate it to free space, and vice versa receive the light from free space and couple it to an IPC.

In our previous study [17], a novel patch nano-antenna was proposed which could be fed by a hybrid plasmonic waveguide through matching of both the wave impedance and operational mode [17]. However; the directivity of the antenna was limited to 5 dBi, due to the small foot-print of the patch antenna.

To achieve higher directivity, here, a novel hybrid plasmonic leaky-wave antenna is proposed for operation at the standard telecommunication wavelength of 1550 nm. The antenna designed here transforms a guided mode into a radiation mode, thus having a vertical radiation pattern. The developed antenna benefits from high directivity advantage of leaky-wave antennas, and low loss properties and confinement of hybrid plasmonic structures, thus having a higher efficiency than plasmonic antennas [14, 18, 19], and a smaller size than dielectric antennas [20, 21]. To be able to

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integrate the optical antenna with other elements in an opto-electronic circuit, the antenna is designed in such a way to be fabricated by standard CMOS fabrication techniques.

Since the proposed device can convert radiating field to guided waves and vice versa, it can have several applications. Specially two antennas (one as transmitter and another as receiver) can be fabricated on different layers of an optical chip to provide inter-chip optical communication. Since the antenna is highly directive, it can provide an efficient optical interconnect. Also the device can be used to enhance the absorption enhancement in photo detectors, and solar cells (after scaling to operate at solar spectrum wavelengths).

2. ANALYSIS AND DESIGN

The structure of the proposed optical antenna is shown in Fig. 1. As shown in this figure, the antenna is designed based on the hybrid plasmonic structure [22–26]. These structures are developed by implementing a material with low refractive index (SiO_2), between a metal (Ag), and another material with higher refractive index (Si). This structure supports a guided plasmonic TM mode, with high confinement inside the material with lower refractive index [22–26]. When the guided hybrid plasmonic mode enters to the antenna, it transforms to a radiating mode due to the periodic slots provided in the design (See Fig. 1).

Since the structure supports a TM plasmonic mode, the electric field has components both in the y, and z directions [27]. However; as shown in the previous work on the plasmonic patch nano-antenna [17], the y component is one order of magnitude bigger than the z component. This difference comes from the big difference between the refractive index of the dielectric (SiO_2) and that of the metal (Ag). Since the z component is much smaller than the y component, in this analysis we can neglect it. The y component of the electric field inside the antenna can be written in terms of a Fourier series expansion

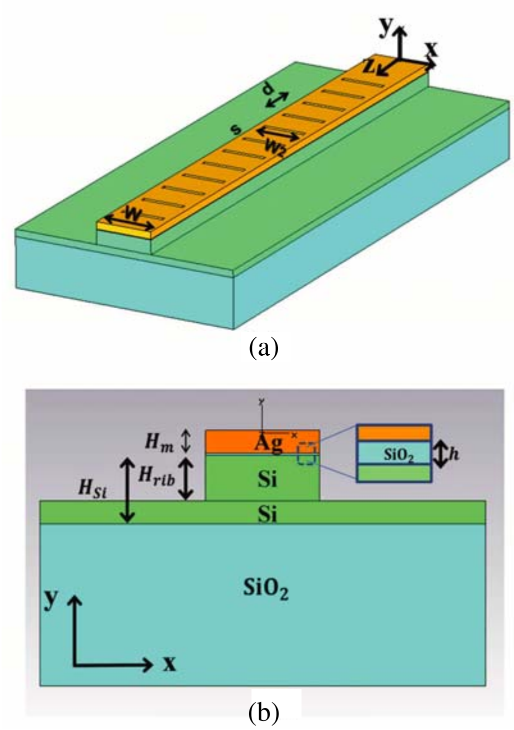

Figure 1. Leaky-wave optical antenna. (a) Perspective view. (b) Side view.

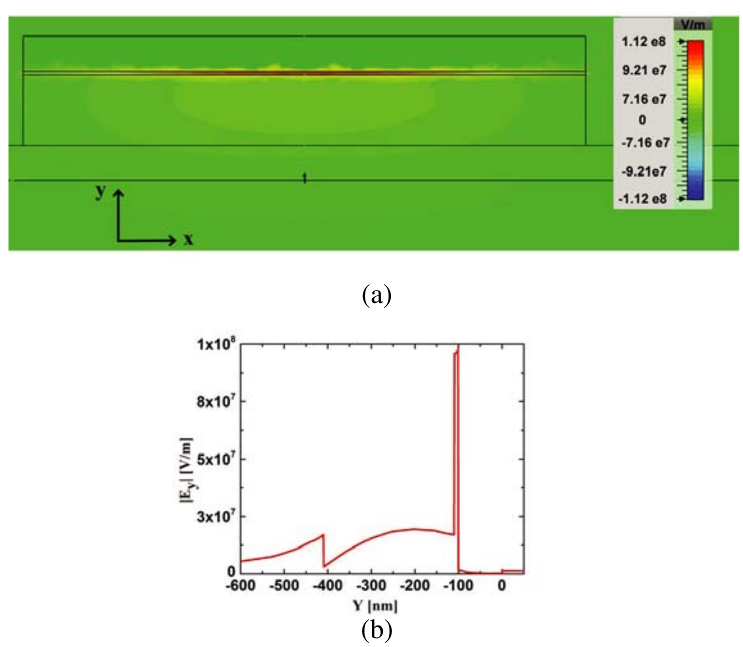

Figure 2. Mode configuration: dominant component of the electric field, $|E_y|$ (a) in two dimensions at the input of the traveling wave antenna ($z = 0$) and (b) in one dimension when $x = 0$, and $z = 0$.

as [28]:

$$E_y(x,z) = \sum_{n=-\infty}^{\infty} E_{y,n} e^{-jk_{z,n}z} \quad \text{where} \quad k_{z,n} = j\alpha + \beta_{z,0} + 2n\pi/d \tag{1}$$

where n is the order of the Floquet spacial harmonics, $k_{z,n}$ the wavenumber of the Floquet mode of order n, $E_{y,n}$ the weight of the n-th mode, d the periodicity of the slots (See Fig. 1), and $\beta_{z,0}$ the wavenumber of the hybrid plasmonic mode of the waveguide when the slots do not exist. As shown in (1), the slots generate additional modes with wavenumbers that can be controlled by periodicity of the slots, d. By controlling the design parameters, one can make the wavenumber of some of these modes to be smaller than the wavenumber of the surrounding media (Air in this design). The modes with wavenumber smaller than that in the air are leaky modes and makes the radiation beam. Here, the antenna is designed in such a way that only one Floquet mode, $n = -1$, generates the radiation beam, and other n-indexed Floquet modes are evanescent waves:

$$|\text{real}(k_{z,-1})| < \beta_0, \quad \text{or} \quad |n_{eff}\beta_0 - 2\pi/d| < \beta_0 \tag{2}$$

where β_0 is the wavenumber in the air and n_{eff} the effective refractive index of the hybrid plasmonic waveguide without the slots.

A comprehensive study was done in [17] on n_{eff}. It was shown that n_{eff} is dependent on W and h, and also using CST simulation and fitting tools in Matlab, the following formula was derived to calculate n_{eff}. The other parameters and dimensions used to derive this formula are as follows: $\lambda_0 = 1550\,\text{nm}$, the permittivity of Ag at this wavelength is $\epsilon_{Ag} = -129 + j3.28$, and the dimensions shown in Fig. 1(b) are $H_m = 100\,\text{nm}$, $H_{rib} = 200\,\text{nm}$, and $H_{Si} = 300\,\text{nm}$.

$$n_{eff} = \sqrt{\frac{\epsilon_d \epsilon_m}{\epsilon_d + \epsilon_m}} F(W,h) \qquad F(W,h) = \frac{1 + 1798W + 3114h + 10.55Wh}{32300 + 759.7W + 3337h + 10.55Wh} \tag{3}$$

Using (3), for $W = 1600\,\text{nm}$, and $h = 10\,\text{nm}$, the real part of n_{eff} is calculated to be equal to 3.04. Using this value and considering the relationship in (1), d is chosen as $d = 550\,\text{nm}$. We chose this value of d, to satisfy the condition in (1) and also to get the highest possible directivity for the radiation pattern. The other dimensions in Fig. 1 are selected as follows: $W_2 = 1200\,\text{nm}$, and $S = 30\,\text{nm}$. These dimensions are selected based on the results of the parametric study performed using CST full-wave simulation to achieve the highest possible directivity.

3. NUMERICAL RESULTS

To verify the performance of the designed antenna, the optical hybrid plasmonic leaky wave antenna is numerically analysed using 3-dimensional full-wave numerical simulation. The simulation is performed using CST microwave studio. The results of this simulation are illustrated in Figs. 2–5. To investigate the mode configuration, Fig. 2 illustrates the magnitude of the electric field, E_y at the cross section of input port of the traveling wave antenna. As shown in this figure, the field shows a high confinement in the thin SiO_2 layer. The mode configuration is exactly what we expect for a hybrid plasmonic TM mode [22–26].

Figures 3 and 4 illustrate S_{11} (the ratio of the reflected wave to the incident wave at the input port) and S_{21} (the ratio of the wave reached at the end of the antenna to the incident wave) respectively, as a function of the operation frequency and also the corresponding wavelength. The results are achieved for an antenna with 12 slots, $N = 12$. In this simulation, for the permittivity of the silver, ϵ_{Ag}, the data in [29] is used which considers also the frequency-dependency of this parameter. The return loss, S_{11} of the leaky-wave optical antenna, is around $-15\,\text{dB}$ at the wavelength of 1550 nm (193.5 THz), meaning that less than ten percent of the light will be reflected at the input port. The bandwidth of the antenna, corresponding to $S_{11} < -10\,\text{dB}$, is 16 THz, or 8%. The equivalent wavelength bandwidth has the range of 1449 nm–1578 nm, which completely covers both standard optical communication bands of S and C. According to the results of Fig. 4, S_{21} is less than $-10\,\text{dB}$ in the whole frequency range, showing that only a small part of the light reaches the end of the waveguide, and most of the light radiates away from the antenna.

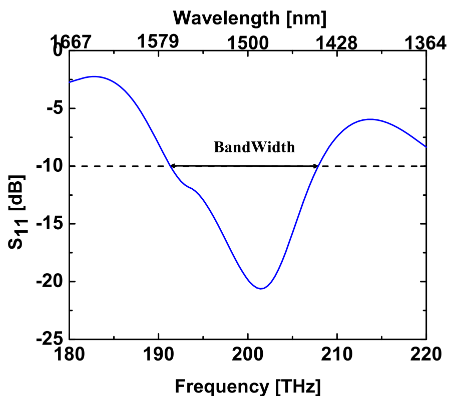

Figure 3. The ratio of the re ected wave to the incident wave at the input port, S_{11}.

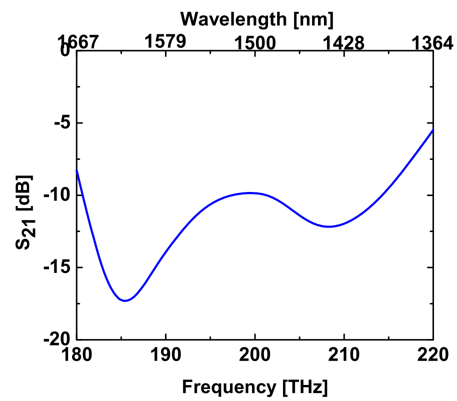

Figure 4. The ratio of the wave reached at the end of the antenna to the incident wave, S_{21}.

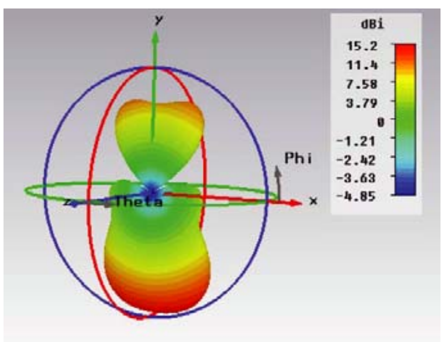

Figure 5. 3-dimensional Radiation pattern of the leaky-wave optical antenna.

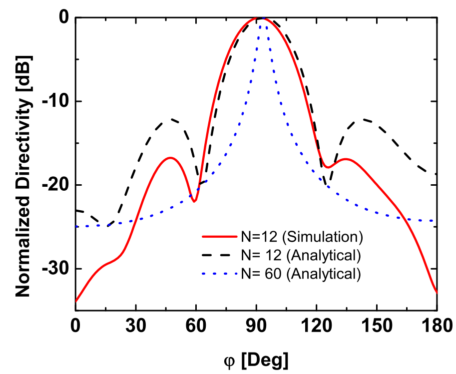

Figure 6. The normalized directivity for different numbers of slots.

The radiation pattern of the leaky-wave optical antenna is shown in Fig. 5. As shown in Fig. 5, a directivity of 15.2 dBi; a very high value for this size of antenna and for only 12 slots is achieved. The total efficiency of the antenna, defined as the ratio of the radiated power over the total power entering the waveguide, is numerically calculated as 82%, at the wavelength of 1550 nm. Since the insertion loss (S_{21}), and return loss (S_{11}) of the antenna at this wavelength are -11.4 dB (corresponding to 7%), and -15 dB (corresponding to 3%) respectively, the dissipation loss can be calculated as 8%. The reason behind this low dissipation loss is that here we have designed our antenna based on hybrid plasmonic structures which are known to provide lower loss when compared to pure plasmonic structures [22–26].

Here the antenna is designed to have only $N = 12$ slots. As shown in [20], it is predicted that increasing the number of slots will result in even higher directivity.

For the case of using more slots, due to the high aspect ratio between the antenna and slot dimensions, large number of meshes is required, and the simulation can't be done accurately using a typical computer. Therefore; here the case of 60 slots is investigated analytically. Using the well known formula in [28], the array factor of the antenna can be calculated analytically as:

$$AF(\varphi) = \sqrt{\frac{1 + e^{-2\alpha L} - 2e^{-\alpha L}\cos((k_0\cos(\varphi) - \beta)L)}{1 + e^{-2\alpha L} - 2e^{-\alpha L}\cos((k_0\cos(\varphi) - \beta)d)}} \tag{4}$$

where β is the propagation constant of the leaky mode, α the attenuation factor, and L the total length of the leaky wave structure, which is equal to $L = Nd$ in this design. To be able to calculate the array factor for different number of slots, the propagation and attenuation constants are extracted from the numerically calculated Electric field using the same method explained in [20]. β is extracted from phase and α is extracted from the magnitude of the y component of electric field when traveling through the leaky-wave antenna. The extracted values are as $\beta = 2.49 \times 10^5\,\mathrm{m}^{-1}$ and $\alpha = 19.54 \times 10^4\,\mathrm{m}^{-1}$. Using these values and (4) the normalized directivity of the antenna is calculated for $N = 12$, and $N = 60$. The results are shown in Fig. 6. In this figure, the analytical results are compared with numerical results for $N = 12$, to verify the accuracy of the analytical method. As shown in Fig. 6, a much directive pattern will be achieved when increasing the number of slots to 60.

4. CONCLUSION

A novel hybrid plasmonic optical leaky wave antenna is designed to provide a highly directive optical radiation beam. Numerical results illustrate a highly directive pattern with directivity of 15.2 dBi, a wide frequency bandwidth of 16 THz, or 8%, and a high efficiency of 82%. The proposed antenna is designed to be compatible with plasmonic waveguides and can also be fabricated using standard CMOS processing and therefore can be easily integrated with other elements in a photonic integrated circuit (PIC). The proposed device can have application in integrated optical interconnects, highly-integrated optical beam-steering devices such as active LIDARs, and solar cells with high efficiency.

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