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Plasmonic-Solitonic Coupling Structure

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Abstract

The applications of optics, in particular non-linear optics, have joined the electrical ones in many contexts, often equaling or exceeding them thanks to the characteristics ensured by the physical nature of light such as high speed of propagation and low losses. In recent years, nanotechnologies combined with plasmon propagation are shaping a new development scenario that touches areas such as medicine, robotics or neurobiology. In fact, nano-devices are able to reproduce a very large number of functions ensuring very small dimensions. Among these, the applications of surface plasmon polariton waves are becoming more and more important, thanks to their peculiar behavior both as an electric wave and as a light wave. In this work we present an innovative structure consisting of a nano metallic waveguide on which it is possible to propagate a surface-plasmon-polariton signal at the interface with a photorefractive dielectric material. At the end of the guide, the diffracting light can generate, under suitable conditions, a self-confined light beam (bright-screening-photorefractive soliton). In this way the polariton plasmon waves propagating at the interface are automatically coupled within a soliton-based optical waveguide. By definition, soliton guides have very low propagation losses, opening the possibility of using this type of hybrid interconnection in extended complex circuits, for example as memories, thanks to the intrinsic plasticity of the photorefractive nonlinear refractive index.

Keywords: *Plasmonics, Surface Plasmon Polariton, Nonlinear Optics, Solitonic Applications.*

1. Introduction

The functionality, speed and convenience of semiconductor devices, circuits and components relies on their miniaturization and integration into external devices. Modern electronic devices for information processing and sensors are rapidly reaching the intrinsic limit for processing speed and usable bandwidth. This is a substantial problem that is slowing down new technological developments in many areas of modern science and technology. Encouraging solutions could be established by replacing electronic signals with optical signals, whose speed and bandwidth are much higher. However, a big handicap in the use of light is linked to the limited degree of integration that photonic circuits can achieve due to the large dimension of the usable wavelengths compared to the much smaller dimension of the electron wavelength [2]. This problem is related to the diffraction limit of the waves, which does not allow the confinement in structures much smaller than the wavelength [3], i.e. it is not possible to reach the nanoscale integration.

The adaptation of materials with negative dielectric constant is one of the most convenient approach for circumventing the diffraction limit and achieving confinement of electromagnetic energy (at optical frequencies) into nanoscale domain as compact as a few nanometers[4]. The most immediately applicable materials for this intention are metals below the plasma frequency, for which Plasmon–Polariton waves can be excited at their interfaces with dielectric substrates (SPP-Surface Plasmon-Polariton). Characteristics of SPP's is the co-existence of optical and electronic waves, that can interact with CMOS-based electronics maintaining optical nature and properties [5]. By exploiting plasmonics, it is possible to realize subwavelength devices, increasing the confinement while maintaining all the optical properties and electronic integrability [6]. The high propagative losses of the SPPs strongly limits any long propagations and consequently the achievable circuit complexity [7]. Furthermore, the rigid geometry of the metal structures that support the SPPs does not allow the realization of plastic circuits, ie self-assembling and self-aligning systems as it is possible to realize with completely optical systems [13].

The possibility of inducing plastic systems also in plasmon circuitry would be a huge technological step forward, solving important technical problems such as the creation of both random access (RAM) and read-only (ROM) memories[9], the interconnection of distant portions of the circuit [10-11] for both inter and intra chips, communications big data analysis [12] etc....

Using a hybrid approach, in the present work we extend the plasmonic possibilities by direct coupling it with photonic systems: in particular, we study the excitation of a self-confined optical beam (spatial optical soliton) by an SPP wave. We considered a thin metallic layers deposed on a photorefractive substrate. The metal-dielectric interface supports SPP waves that propagate along it until it ends. At this point, the SPP waves diffract within the photorefractive substrate. However, if the experimental conditions allow the excitation of photorefractive screening solitons [14] the diffracting light can self-confine, giving rise to a self-confined beam. Such beam can act as if it were a waveguide [15-16], carrying the signals transported by the SPP waves far from the metallic support.

This innovative hybrid interconnection opens up huge application perspectives, for both memory and signal processing purposes.

2. **Model and Method**

The geometry of the plasmon-soliton coupling system is shown in figure 1. A metallic stripe as thick as 0.5μm and 2μm long, is deposited onto a photorefractive crystal. Here, we have considered Strontium Barium Niobate crystals as photorefractive media.

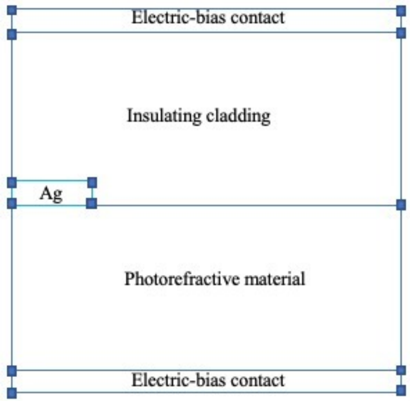

Figure 1: Schematic representation of the simulated structure. The scale is in micron.

On the top, an insulating dielectric cladding isolates the metallic stripe from the higher electrode of a capacitor. The capacitor surrounds the whole structure, and it is dedicated to applying the electric bias necessary to support screening photorefractive solitons. SPP propagates at the interface between the metallic stripe (met) and photorefractive material (PR). The supported SPP waves has the following wavevector moduli:

$$k_x = \frac{\omega}{c}\sqrt{\frac{\varepsilon_{met}\varepsilon_{PR}}{\varepsilon_{met}+\varepsilon_{PR}}} \qquad (1)$$

in the propagation direction and

$$k_{z,j} = i\frac{\omega}{c}\sqrt{\frac{\varepsilon_j^2}{\varepsilon_{met}+\varepsilon_{PR}}} \qquad (2)$$

in the direction orthogonal to the interface. Here the j index describes both met and PR.

When the SPP wave reaches the end of the metallic stripe it diffracts inside the photorefractive medium.

Here, electrons from donor states N_D can be excited in the conduction band [17] leaving a local distribution of ionized donors $N_D{}^i$:

$$\frac{dN_D^i}{dt} = \sigma F\left(N_D - N_D^i\right) - \gamma n N_D^i \qquad (3)$$

where σ describes the absorption cross section of donors, F the photon flux of the diffracting light and γ the probability that a free electron in the conduction band binds to an ionized donor reconverting it into a not-ionized state. As a consequence, a space charge density is generated, constituted by free electrons (n) and ionized donors:

$$\rho(r,t) = e\left[-n(r,t) + N_D^i(r,t)\right] \qquad (4)$$

where e is the electron charge. We have neglected any acceptor distribution in eq. 4 not to weigh down the model. Free electrons can move due to a local diffusion (Flick's law) or due to a conduction induced by the local electric field, constituting a current density j whose expression is:

$$\vec{j}(r,t) = \vec{j}_{conduction} + \vec{j}_{diffusion} = -en\mu\vec{E}(r,t) + k_B T\,\mu\,\vec{\nabla}n \qquad (5)$$

where μ describes the material conductivity, k_B the Boltzmann constant and T the absolute temperature. The current density should very the charge-continuity law:

$$\vec{\nabla}\cdot\vec{j} + \frac{d\rho}{dt} = 0. \qquad (6)$$

Please note that locally an electric field is present, which is the linear combination of the applied bias and the charge induced field:

$$\vec{E} = \vec{E}_{bias} + \vec{E}_{induced} \quad (7)$$

This induced field can be calculated using the well-known Gauss theorem:

$$\vec{\nabla} \cdot \varepsilon \vec{E}_{ind} = \rho. \quad (8)$$

The induced charge movement is such that the field induced by it locally screens the bias field. For this reason, the induced field is often also called the screening one.

The screening effect is indeed fundamental in order to be able to excite bright solitons: the application of a static electric field varies the dielectric tensor of the material through the electro-optic effect:

$$\Delta\overleftrightarrow{\eta} = \Delta\overleftrightarrow{\left(\frac{\varepsilon_0}{\varepsilon}\right)} = \Delta\overleftrightarrow{\left(\frac{1}{n^2}\right)} = \overleftrightarrow{r} : \vec{E} \quad (8)$$

that applied to the SBN crystal gives:

$$n_z = n_e - \frac{1}{2} n_e^3 r_{33} E_z \quad (9)$$

where z is the optical axis and ne is the extraordinary refractive index. As you can see, the electro-optic effect reduces the refractive index ($\Delta n<0$) and, consequently, the light cannot confine withing this variation path. The application of the external bias reduces the refractive index everywhere but where it is screened. Here the refractive index remains high, constituting a trajectory where now $\Delta n>0$ (screening bright solitons [14]).

For an SBN crystal, the donor density N_D is of the order of 10^{19} cm^{-3}, the absorption cross section σ=1.6 10^{-11} cm^2 (@ λ=532nm), the electron mobility μ=0.01 cm^2/Vs and the electron-hole recombination rate γ=5 10^{-8} cm^3/s.

3. Results and discussions

The metallic stripe supports the propagation of a SPP wave at the interface with the substrate, as shown in fig.2. The large thickness of the stripe does not allow the coupling between the lower and the upper interfaces: consequently, the SPP wave remains confined at the interface below. The strong confinement near the interface produces a high intensity of the electromagnetic field which is represented in red color in the figure. As soon as the SPP arrives to the end of the metallic stripe, it is no more confined and it gets diffracted into the photorefractive substrate.

In order to excite the photorefractive screening nonlinearity and consequently to guarantee a self-confinement of this diffracted light, an electric bias must be applied across the photorefractive medium, as theoretically shown in the previous paragraph. For this purpose, a bias voltage is applied to the metallic electrodes on the top and on the bottom of the whole device (fig.1). In order to ensure an homogeneous electric field across the whole structure, we have fixed a +V voltage at the top, a -V voltage at the bottom and V=0 (ground) at the metallic SPP stripe.

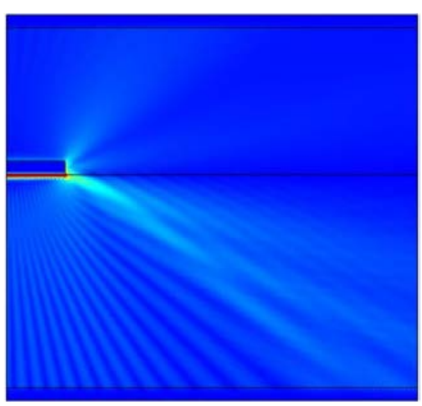

Figure 2: Plasmon propagation and its diffraction.

Such procedure did allow us to obtain a smooth and almost constant electric bias in the volume where the diffracted light should self-confine (fig.3).

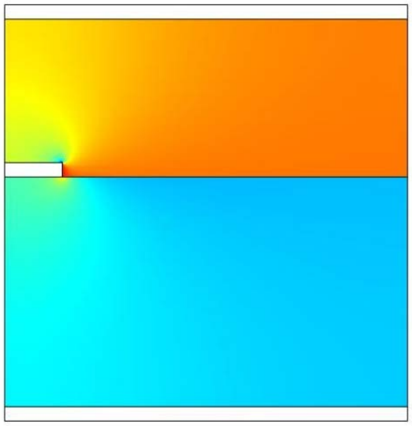

Figure 3: Distribution of the bias field across the whole device.

Please note that at the very edge of the metallic stripe the effect of the tip generates a very high electric field point which however normalizes very quickly. This point of high intensity aids in soliton formation, pushing the photoinduced electrical charges to separate and to screen out the applied bias, allowing a positive modulation of the refractive index.
A characteristic aspect of our structure is the possibility of changing the diffraction angle of the light beam using the electric bias field as a degree of freedom. The curvature of the diffracted light is indeed affected by the bias as shown in fig.4. In this way it is possible to direct the formed soliton according to directions that are more congenial to one's purposes. In the figure we show how the distribution of light changes when the standard voltage value that we used for the formation of the soliton is doubled and tripled.

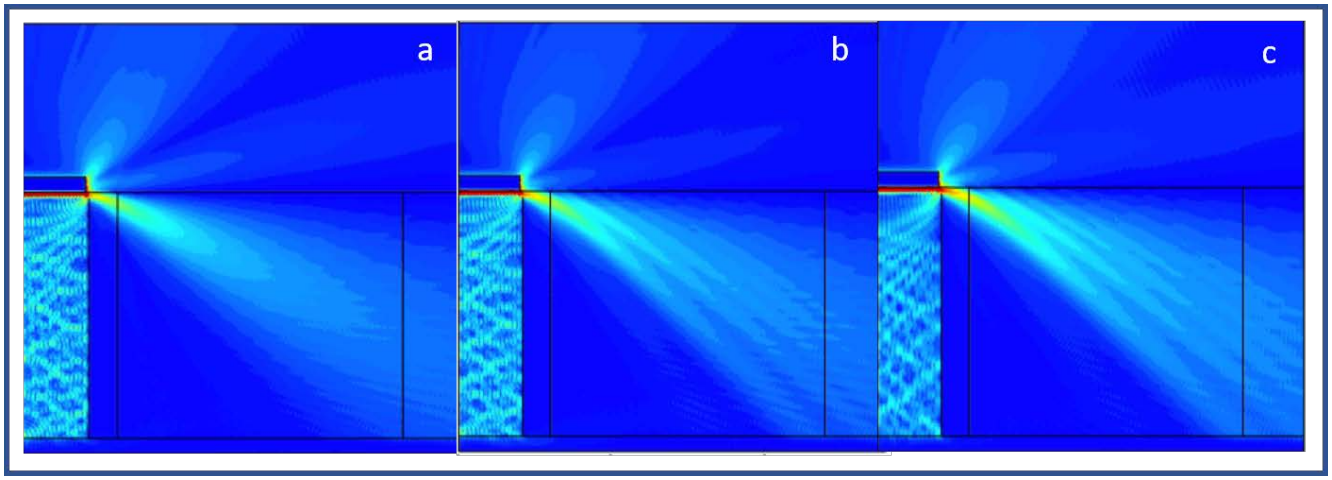

Figure 4: Tilting the diffraction angle of the light for different voltages: DV (a), 2DV (b), 3DV (c) between electrodes.

By letting the time pass, the diffracted light excites free carriers from donor states (eq. (3)) inducing the photorefractive nonlinearity. As a consequence, a local electric field is induced that screens the applied bias. The electro-optic effect will reduce the refractive index across the whole sample because of the external bias, but where the induced local field screens the bias (fig.5 a-e). In this volume the refractive index will be higher with respect to the surrounding, allowing light first to selfocus and, later on, to self-confine (fig.5 f-j). This process depends on the number of excited charges and consequently grows up with time. Fig.5 shows the induced screening field and the light selfconfinement at different temporal steps (50ns, 100ns, 150ns, 200ns and 250ns) of charge integration.
It should pointed out that, as time increases, the amplitude of the screening field increases and, consequently, a better light self-confinement occurs that, consequently, increases the light intensity that speeds up the process and so on…. Such recursive feedback process becomes more and more efficient, making the whole system to rapidly stabilize, at about 250ns, on a clean self-confined beam (the soliton solution in fig. 5j).

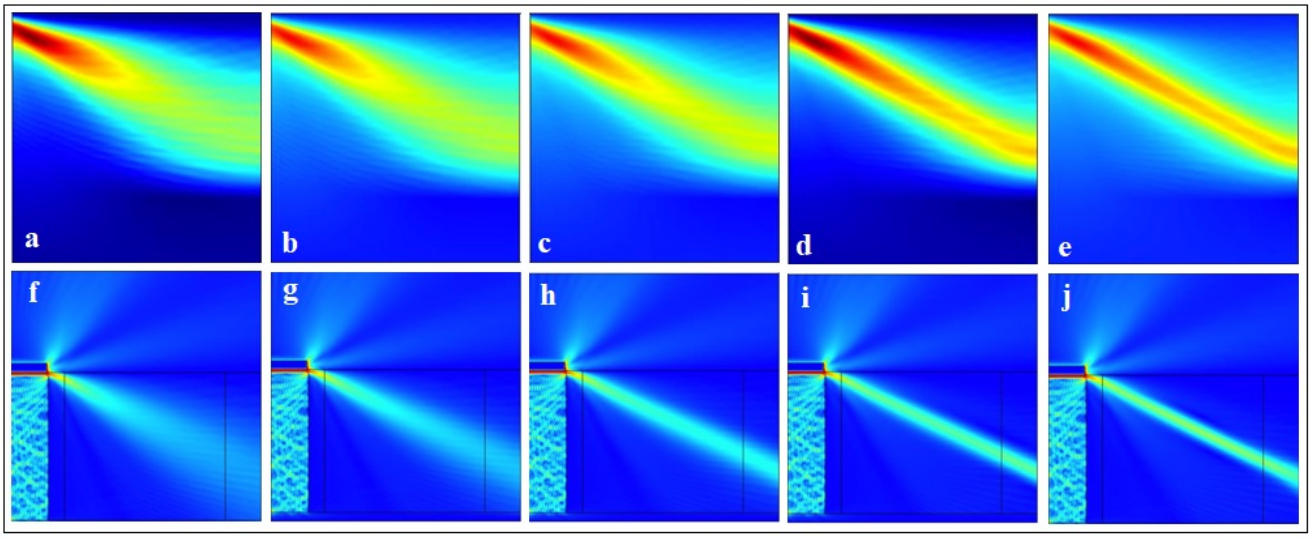

Figure 5: Screening field a-e, and Modulus of the electric field of the beam f-j at time steps of 50 ns, 100 ns, 150 ns, 200 ns and 250 ns respectively.

3. Conclusions

In this article we have demonstrated for the first time the possibility of generating a soliton channel starting from a metal strip that supports SPP waves. The soliton channel can act as a self-confined waveguide, with important application functionalities for both signal processing and memory creation. The very low losses of the soliton waveguides allows to compensate for the high plasmonic losses, extending their propagation. We are currently studying plasmonic circuit geometries interconnected through soliton guides that can be written and erased as needed. The proposed system is therefore extremely versatile and robust, both in terms of stability and reproducibility.

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