Nanophotonics in Modern Communication Systems – Feasibility of Plasmon-Polariton Waveguides in Optical Networks

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Abstract — **Use of surface-plasmons-polaritons has become a potential way to develop optical components below the diffraction limit. This paper reports the feasibility of some plasmon-polariton waveguides in optical communication systems. Combinations of metal elements of different geometry are theoretically analyzed. They can serve as building blocks in future nanophotonic systems. The spectral responses of these structures show they can be used as frequency selective components in optical communication windows for wavelength division multiplex applications.**

Keywords – **Nanophotonics, surface-plasmon-polaritons, subwavelength waveguiding structures.**

I. INTRODUCTION

A continuous miniaturization of conventional optical components based on fiber optics is not straightforward because it is restricted by the diffraction limit of light. A promising way to overcome such limit is manipulation of surface-plasmon-polaritons (SPPs). These electromagnetic waves propagate along a metal-dielectric interface by a resonant interaction between photons and free electrons at the conductor surface. The wavelength of a SPP wave is many orders less than the wavelength of light and, as consequence, has the ability to confine and enhance electromagnetic fields at nanoscale. The paper [1] published in Nature is considered as a milestone of plasmonic technology

The advances in nanostructurization of metals have allowed the exploration of SPP properties showing the feasibility to develop nanophotonic networks. From a suitable design of metal-dielectric interface, one may confine light into a nanosized area and transmit the optical signal over micrometric distances with low attenuation. These features are not only very attractive for introduction of plasmon devices in current optical technology, as optical-fiber-based networks, but pave a way to implement a new generation of all-optical components for usage in nanoprocessing modules.

In information technology, SPPs are a suitable choice to implement photonic circuits with subwavelength dimensions. Since the beginning years of 21 century, there was a high increase of researches in the field of nanoplasmonics and its applications in communication systems.

The most basic plasmon-polariton waveguides are composed by stacks of metal strips and dielectric layers [2]. The SPP mode confinement of these waveguides may be manipulated by introduction of grooves or regular gratings along the metallic slab. Other configurations include periodic arrays of metallic nanoparticles embedded in a dielectric matrix [3]. With these structures, a large variety of optical components has been implemented such as resonators, couplers and interferometers, to name a few. For instance, plasmon ring resonators may be used as building blocks of add-drop filters [4] and silver-air-silver multilayer systems can provide coupling efficiency above 80% with optical fibers [5].

This presentation reports the potentials of SPP waveguides applications in optical communication systems. Some periodic nanostructures are analysed as examples of applicability of these devices in photonic networks.

II. FUNDAMENTALS OF SURFACE-PLASMON-POLARITON PROPAGATION

Surface-plasmon-polaritons are electromagnetic waves that propagate at the interface between a dielectric and a conductor. The mechanism of SPP generation essentially comprises the coupling of electromagnetic fields to the collective electron plasma oscillation at the conductor surface. Fig. 1 shows the evanescent profile of the field distribution of a SPP wave.

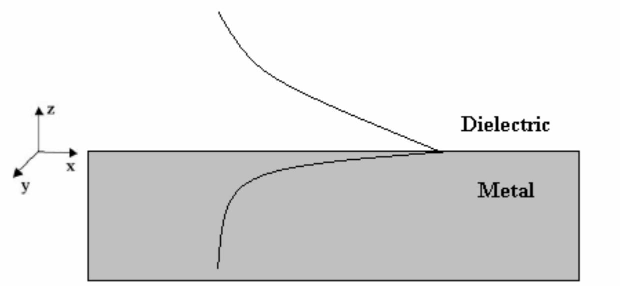


Fig. 1 – Field distribution profile of a SPP wave.

The Maxwell's equations are the starting point to investigate SPP propagation conditions. To carry out such analysis, the dispersive character of metals at optical frequencies must be taken into consideration. The dispersion Drude formulation (1) constitutes a simple but powerful modeling within this framework:

$$\varepsilon(\omega) = 1 - \frac{\omega_P^2}{\omega(\omega - j\Gamma)}, \tag{1}$$

where $\varepsilon(\omega)$ is the dielectric function written in the frequency domain; ω is the angular frequency; ω_P^2 is the plasma frequency; j is the imaginary unit; Γ is the collision frequency. Notice that (1) was obtained by considering electromagnetic fields with $e^{j\omega t}$ time-harmonic variation.

By manipulation of Maxwell's equations, it is demonstrated that only SPP TM modes are allowed at the metal-dielectric interface. Prohibition of TE waves may be intuitively understood regarding that longitudinal electric field component is necessary to excite electron plasma oscillation.

For the case showed in Fig. 1, the field components equations needed to solve are given by (2)-(3). The corresponding set of solutions is expressed by (4)-(9).

$$E_x = -i\frac{1}{\omega\varepsilon_0\varepsilon}\frac{\partial}{\partial z}H_y, \tag{2}$$

$$E_z = -\frac{\beta}{\omega\varepsilon_0\varepsilon}H_y. \tag{3}$$

For z>0, we have:

$$H_y(z) = A\exp(-k_d z)\exp(-j\beta x), \tag{4}$$

$$E_x(z) = jA\frac{k_d}{\omega\varepsilon_0\varepsilon_d}\exp(-k_d z)\exp(-j\beta x), \tag{5}$$

$$E_z(z) = -A\frac{\beta}{\omega\varepsilon_0\varepsilon_d}\exp(-k_d z)\exp(-j\beta x), \tag{6}$$

and for z<0:

$$H_y(z) = B\exp(k_m z)\exp(-j\beta x), \tag{7}$$

$$E_x(z) = -jB\frac{k_m}{\omega\varepsilon_0\varepsilon_m}\exp(k_m z)\exp(-j\beta x), \tag{8}$$

$$E_z(z) = -B\frac{\beta}{\omega\varepsilon_0\varepsilon_m}\exp(k_d z)\exp(-j\beta x). \tag{9}$$

In (2)-(9), A and B are arbitrary constants, ε_0 and μ_0 are the permittivity and permeability of vacuum, ε_d e ε_m are the permittivity of dielectric and metal, respectively, β is the propagation constant and

$$k_i = \sqrt{\beta^2 - \omega^2\mu_0\varepsilon_0\varepsilon_i}\ ,\ i=m,d. \tag{10}$$

The continuity of the electric and magnetic field components parallel to the interface yields the SPP dispersion relation (9), which is the central result of this analysis:

$$\beta = \omega\sqrt{\varepsilon_0\mu_0}\sqrt{\frac{\varepsilon_m\varepsilon_d}{\varepsilon_m + \varepsilon_d}} \tag{11}$$

The dispersion relation shows the momentum mismatch that must be overcome in order to couple light and plasma oscillations. As a consequence, techniques of phase matching such as Bragg grating or prisms are required for SPP excitation. The normalized dispersion relation for SPP propagation at the interface between a Drude metal with $\omega \gg \Gamma$ and silica is graphically depicted in Fig. 2. SPP bounded modes correspond to the dispersion curve at the high side of the light line of silica. The transparence regime, i. e., the spectral range where metals present negligible polarization effects, comprises the part of the dispersion curve for which $\omega > \omega_P$. The gray region corresponds to the spectral range where SPP modes are not allowed.

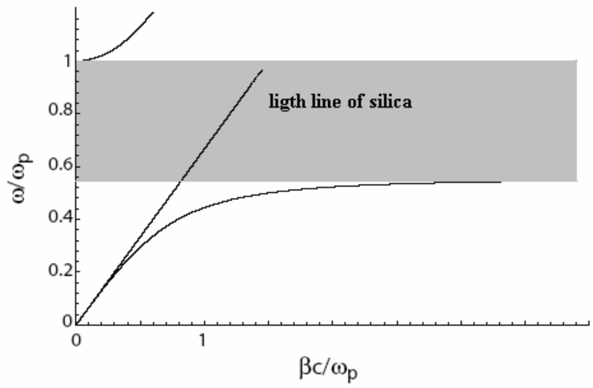


Fig. 2 – Normalized dispersion curve of SPP propagation at the interface between silica and a metal with $\omega \gg \Gamma$.

The above theory launches the basis to understand energy transport with concentration of light in subwavelength dimensions. The following section links these principles to the operation features of optical waveguides where guidance of electromagnetic power is described in terms of surface-plasmon-polaritons.

III. SPP Mode Propagation in Nanoscale Structures

In this section we calculate frequency responses of different nanoscale structures, namely a periodic arrangement of metallic inclusions embedded in free space. The results were obtained by numerical simulation carried by the Finite-Difference Time Domain (FDTD) Method for dispersive media [6]. The peculiarity of this approach is the presence of the polarization current density (12) in the update equation for electric field by virtue of dependence on frequency of the dielectric function:

$$\overline{J}_P^{n+1/2} = \left(\frac{2}{2+\Gamma\Delta t}\right)\overline{J}_P^{n} + \frac{\varepsilon_0\omega_P^2\Delta t}{4+2\Gamma\Delta t}\left(\overline{E}^{n+1} + \overline{E}^{n}\right) \tag{12}$$

In (12), Δt is the time increment e n is the time step.

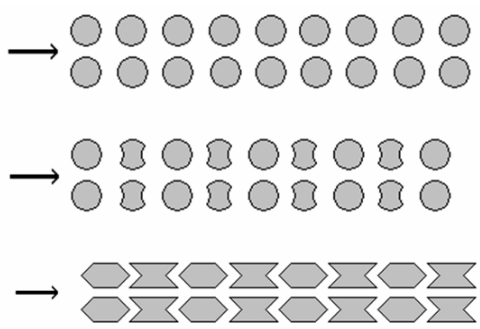
The wideband excitation source is defined as a Gaussian beam with the central wavelength of 600 nm and the waist of 200 nm, employed here to simulate normal incidence via the Total Field/Scattered Field method [6].

The metallic inclusions are silver nanorods (simplexes) with the longer dimension adopted for each inclusion being 20 nm, 25 nm, and 30 nm for the structures on the top, middle, and bottom rows of Fig. 3, respectively. The electric field intensity along these structures is also shown in this figure. The Drude parameters of silver are listed in Table I.

TABLE I. CONSTANTS OF DRUDE MODEL

Constants of Drude model	**Values**
ω_P	13673 THz
Γ	27.35 THz

Although the nanorods are in subwavelength dimensions, scaterring of light by diffraction is avoided since plasmon resonances are reached. Confinement and guiding of electromagnetic energy depends on the plasmon coupling between two consecutive rods.



(a)

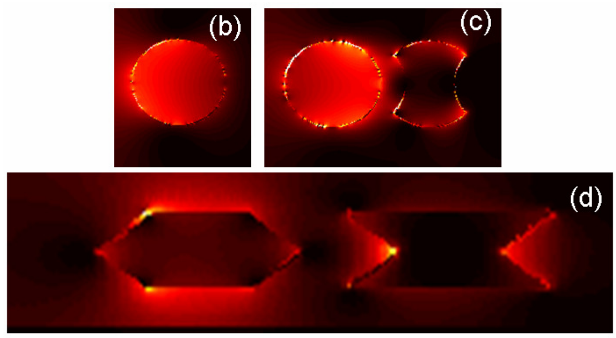
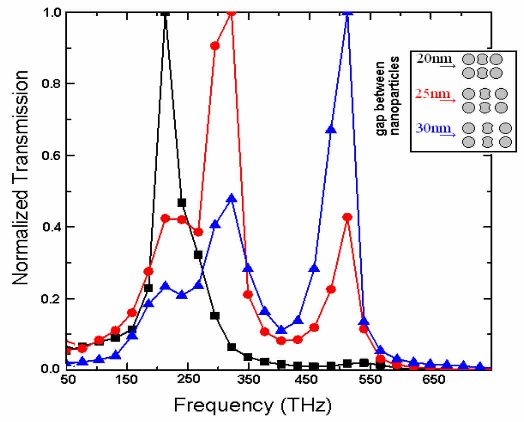
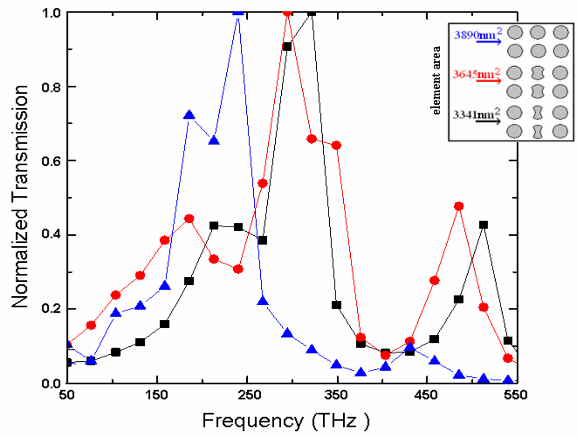


Fig. 3 – (a) Periodic plasmon waveguide composed by cilyndrical nanorods (top row), periodic combination of collapsed and cilyndrical nanorods (middle row) and periodic combination of sharp diamond-like structures (bottom row), the arrows indicate direction of incidence of the electromagnetic power. Electric field intensity is shown in (b)-(d) figures.

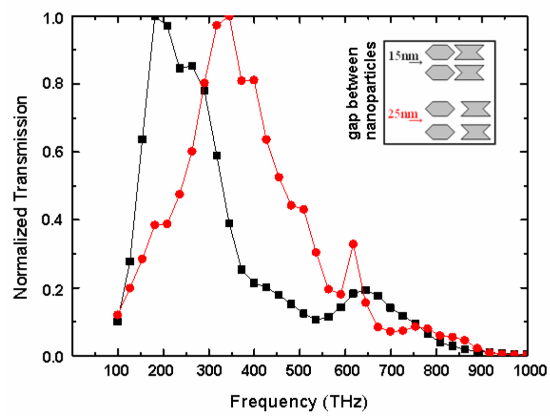
Fig. 4(a)-(d) shows frequency response of the structures depicted in Fig. 3(a). These results comprise variation of the plasmon resonance peaks of each combination with the parameters shown in the insets.



(a)



(b)



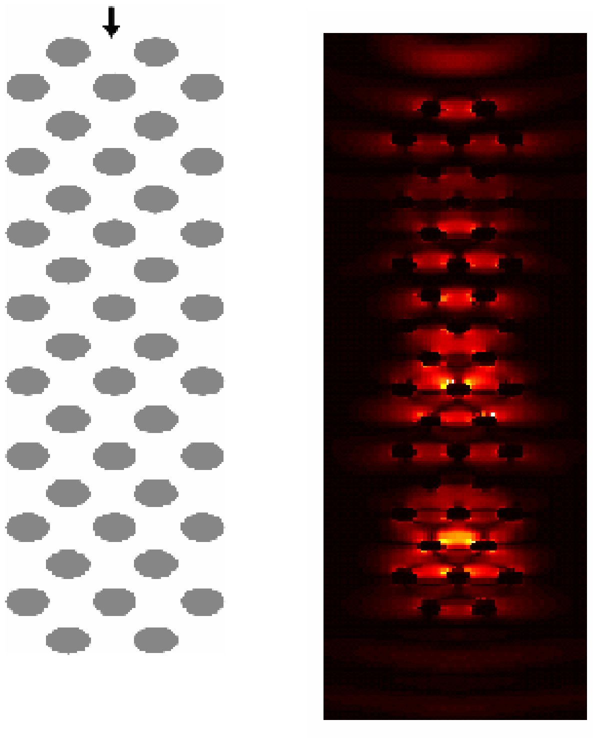
(c)

Fig. 4 – (a) Frequency response obtained with FDTD. The gap between the inclusions is: 20nm (squares), 25nm (circles), and 30nm (triangles). (b) Frequency response o for different element areas. The area is calculated as the sum of the first two consecutive simplexes. (c) Frequency response for the combination of diamond-like simplexes for two gap separations: 15nm (squares) and 25nm (circles).

All the structures in Fig. 4 possess resonance peaks at the optical communication windows. These structures can be utilized to tune a given frequency, which can be quite useful for wavelength division multiplex (WDM) applications. The attenuation factor for the collapsed-cilyndrical nanorod and diamond-like structure combinations are 2.2 db/μm and 2.8

db/μm, respectively. The last case presents larger losses due to major intensity of radiated fields.

The structures shown previously can be used as units for construction of periodic nanophotonic waveguides. As a last example we consider the case of a hexagonal array of cylindrical silver nanorods in free space, as it is schematized in Fig. 5.



(a) (b)

Fig. 5 – (a) Plasmon waveguide composed by silver nanorods in hexagonal lattice. The radius of each nanorod is 5 nm and the lattice constant is 10 nm. The arrow indicates the input port. (b) Power distribution along the waveguide.

The corresponding spectrum of transmitted power is depicted in Fig. 6.

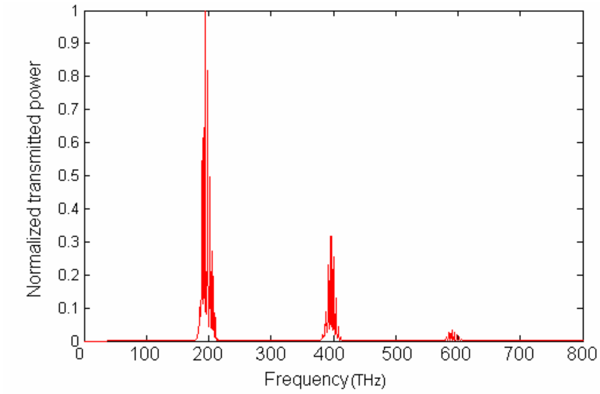


Fig. 6 – Spectrum of the transmitted power in the plasmon waveguide composed by silver nanorods in hexagonal lattice. The power is normalized by the input one.

The transmission peak close to 200 THz demonstrates that such a waveguide can be used as a frequency selective nanophotonic device.

IV. Conclusion

The potentials of plasmon-polariton waveguides for optical communication systems are reported in this paper. The basic theory of SPP mode propagation was presented in order to explain the principle of operation of plasmon devices. In order to show that these structures are feasible to work as optical components, we analysed numerically the frequency response of some plasmon waveguiding structures. The obtained results indicate the usefulness of these devices in WDM applications. Moreover, they could give additional degrees of freedom in the design of frequency selective components.

V. Acknowledgment

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VI. References

[1] W. L. Barnes, A. Dreux and T. W. Ebbesen, “Surface plasmon subwavelength optics”, Nature, vol. 424, pp. 824-830, 2003.

[2] B. Steinberger, A. Honeau, A. Ditlbacher, A. L. Stepanov, A. Drezet, F. R. Ausseneg, A. Leitner and J. R. Krenn, “Dielectric stripes on gold as surface plasmon waveguides”, *Applied Physics Letters,* vol. 8, pp. 1-3, 2006.

[3] S. Gwo and H. Y. Chen, “Gallium-nitride nanorods serves as subwavelength optical media,” *Spie Newsroom*, 2009.

[4] Y. Satuby and M. Oreinstein, “Surface-plasmon-polariton modes in deep metallic trenches-measurement and analysis”, *Optics Express*, vol. 15, pp. 4247-4252, 2007.

[5] R. A. Wahsheh, Z. Lu and A. M. Abushagur, “Nanoplasmonic couplers and splitter,” Optics Express, vol. 17, pp. 19033-19040, 2009.

[6] A. Taflove and S. Hagness, *Computational Electrodynamics: The Finite-Difference Time-Domain Method*, Artech House, Boston, 2005.