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L. Dobrzynski, Abdellatif Akjouj

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L. Dobrzynski and A. Akjouj

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L. Dobrzynski[a)] and A. Akjouj
CNRS-UMR 8520, UFR de Physique, Université de Lille 1, 59655 Villeneuve d'Ascq Cédex, France

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The system presented here enables transmission of almost all the light intensities injected in four input channels into one output channel. It is conceived in the form of a metallic wire with one central hole and four other holes parallel to the central one. The incident light is injected in the four external holes and transmitted to the central one, thanks to appropriate resonant mechanisms between the central hole and each of the four other holes. Each of these mechanisms is constituted by two coupled cavities. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2966340]

The interaction between light and metals attracts a lot of interest, especially for nanostructures on length scales smaller than the wavelength of the light involved. A light wave coupled to free electron oscillations at metal-dielectric interfaces, known as surface plasmon polaritons, can be laterally confined to light energy in nanoscale domain.[1] This attracts tremendous research interest in constructing waveguide structures with nanometric cross section. Several plasmonic waveguiding structures have been proposed such as metallic nanowires,[2] metallic nanoparticle arrays,[3–5] and V grooves in metal substrate.[6,7] Among the structures, those that focus the light into the dielectric core in a metal-insulator-metal sandwich allow the manipulation and transmission of light at the nanoscale. Metal-insulator-metal based plasmon slot waveguides have been shown to provide both long-range propagation and subwavelength spatial confinement.[8] Such waveguides are promising for the design of nanoscale all-optical devices as the numerical and experimental investigations show strong localization, zero bend losses, as well as relatively simple fabrication.[9–11]

The phenomenon of extraordinary light transmission through metallic films perforated by nanohole arrays at optical frequencies was first observed by Ebbesen *et al.*[12] Such structures are expected to have potential applications, such as optoelectronic devices,[13] chemical sensing,[14] and subwavelength optics.[15]

In the present letter, we also address the transmission of light through a metallic film perforated by holes filled with a dielectric material. The holes considered here do not have to present subwavelength dimensions. We just assume that the incident light is transmitted through these holes by excitation of the hole surface plasmons through direct coupling or coherent diffraction by all the individual subwavelength holes acting as elementary scatters.[16]

The phenomenon reported here is an enhanced directional transmission of light injected in four holes and transmitted into the fifth one. This is shown to be possible thanks to resonant couplings between the output hole and the four input ones. Each of the couplings is made out of two interacting cavities.

Figure 1 presents two views of the fiber under study here. Figure 1(a) shows a top view of the metallic fiber with five holes. The central one is the output hole and the other four are the input ones. Figure 1(b) presents a transversal cut of the fiber showing the central output hole and two of the four external input and output holes, as well as the cavities responsible for the resonant coupling between the input and output channels. The input amplitudes are labeled as i_j with $j=3, 5, 7, 9$ and the output amplitudes as o_j with $j=1-10$.

The coupling cavities are assumed to have all the same ω_0 plasmon eigenfrequencies. The two connected cavities interact between themselves by a coupling strength β_2, and each of them interacts with the two nearest guides by a coupling strength β_1. Of course, in order to interact between themselves and with the channel holes, the thickness of the metal between the cavities and the guides has to be smaller than the usual metal skin depth.

Within the guiding holes, we assume the existence of long wavelength surface plasmons. This surface plasmon dispersion relation can be considered as the long wavelength limit of those of a linear chain of cavities of frequencies ω_0,

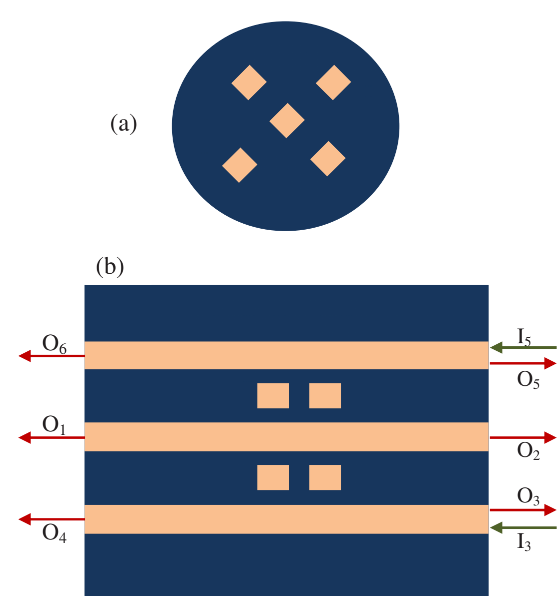

FIG. 1. (Color online) Sketch of the considered fiber structure. (a) The entrance of the four external input channels within the center at the rear of the main output channel. (b) The transversal cut of the fiber showing the central output hole and two of the four external input and output holes, as well as the cavities responsible for the resonant coupling between the input and output channels. The input intensities are labeled as I_i with $i=3, 5, 7, 9$ and the output amplitudes as O_i with $i=1-10$.

[a)]Author to whom correspondence should be addressed. Electronic mail: leonard.dobrzynski@univ-lille1.fr.

with a coupling strength β between the two nearest neighbor ones separated by a distance d. Such dispersion relation is[17]

$$\omega^2 = \omega_0^2 - 2\beta \cos(kd). \tag{1}$$

The long wavelength limit $kd \ll 1$ of Eq. (1) is

$$\omega = ck, \tag{2}$$

where c is the speed of light, which is obtained for $\beta = \omega_0^2/4$ and $d = c\sqrt{2}/\omega_0$.

The above defined problem can now be placed into equations with the help of Green's function method.[5] It is convenient to start with the discrete chains of clusters and then take the long wavelength limit for the guiding holes.

For the same input amplitudes $i_3 = i_5 = i_7 = i_9 = 1$, with the help of the superposition principle, one obtains the output amplitude to be

$$o_1 = 4j\left(\frac{\Gamma^+}{\Delta_S} - \frac{\Gamma^-}{\Delta_{AS}}\right), \tag{3}$$

$$o_2 = 4j\left(\frac{\Gamma^+}{\Delta_S} + \frac{\Gamma^-}{\Delta_{AS}}\right), \tag{4}$$

$$o_3 = o_5 = o_7 = o_9 = -1 + j\left[\frac{j + \tan(kd/2) + 2\Gamma^+}{\Delta_S} + \frac{j - \cot(kd/2) + 2\Gamma^-}{\Delta_{AS}}\right], \tag{5}$$

$$o_4 = o_6 = o_8 = o_{10} = j\left[\frac{j + \tan(kd/2) + 2\Gamma^+}{\Delta_S} - \frac{j - \cot(kd/2) + 2\Gamma^-}{\Delta_{AS}}\right], \tag{6}$$

where

$$\Gamma^{\pm} = -\frac{(\beta_1/\beta)^2}{kd[(kd)^2 - (k_0 d)^2 \pm (\beta_2/\beta)]}, \tag{7}$$

$$\Delta_S = [j + \tan(kd/2) + 2\Gamma^+][j + \tan(kd/2) + \Gamma^+] - 4(\Gamma^+)^2, \tag{8}$$

$$\Delta_{AS} = [j - \cot(kd/2) + 2\Gamma^-][j - \cot(kd/2) + \Gamma^-] - 4(\Gamma^-)^2, \tag{9}$$

and

$$k_0 = \omega_0/c. \tag{10}$$

A maximum of intensity O_1 is transferred to channel one when

$$\frac{\beta_1^2}{\beta\beta_2} \simeq 1. \tag{11}$$

In order to obtain this effect in a large frequency range, it is helpful to choose interactions β_2, β_1, and β to be about the same.

The transferred peak intensity is kept as symmetrical as possible in the function of kd when

$$k_0 d = (1 + 4n_0)\frac{\pi}{2}(n_0 = 1,\ 2,\ 3,\ 4,\ \ldots). \tag{12}$$

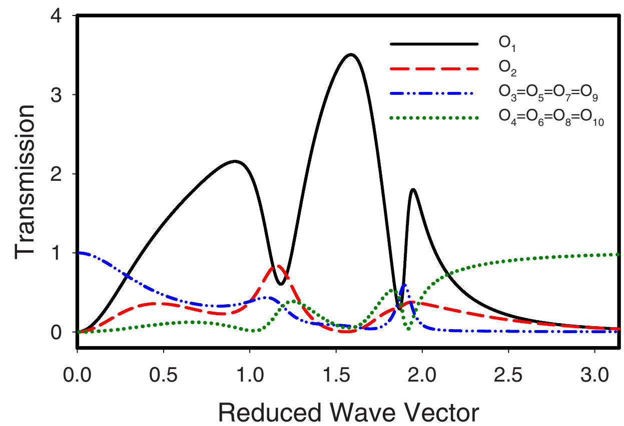

FIG. 2. (Color online) Output-signal intensities as a function of kd. The results were obtained for $k_0 d = \pi/2$.

Figure 2 displays the output intensities corresponding to four unity input amplitudes injected through ports 3, 5, 7, and 9 for $k_0 d = \pi/2$. The central O_1 enhanced transmission is given by the black full line. Note that it overpasses 3.5 at its maximum. The backward reflection O_2 is given by the red dashed line. The other backward reflection $O_3 = O_5 = O_7 = O_9$ is given by the blue dot-dashed line. The direct transmissions $O_4 = O_6 = O_8 = O_{10}$ are represented by the green dotted line. These results show clearly that the special system presented in this letter is able to focus almost all the incident optical intensities from four channels into just one in a large wavelength range.

Attenuation effects were not included in the simple estimations above as they are known to be negligible for surface plasmon propagation inside the dielectric holes.

Many improvements to the present simple model are expected to be included in future studies. The main ones will probably have to deal with the estimation of the interactions between the cavities and the channel holes.[18] It is also possible to increase the intensity enhancement by building fibers with more than four input channels.

Let us also stress that the enhanced transmission effect for plasmons reported here exists for any other waves and particles. Similar systems can be conceived for photons, phonons, magnons, electrons, etc.[19]

[1] W. L. Barnes, A. Dereux, and T. W. Ebbesen, Nature (London) **424**, 824 (2003).
[2] P. Berini, Phys. Rev. B **61**, 10484 (2000).
[3] M. Quintin, A. Leinter, J. R. Krenn, and F. R. Aussenegg, Opt. Lett. **23**, 1331 (1998).
[4] S. A. Maier, P. G. Kik, H. A. Atwater, S. Meltzer, E. Harel, B. E. Koel, and A. A. G. Requicha, Nat. Mater. **2**, 229 (2003).
[5] L. Dobrzynski, A. Akjouj, B. Djafari-Rouhani, J. O. Vasseur, M. Bouazaoui, J. P. Vilcot, H. Al-Wahsh, P. Zielinski, and J. P. Vigneron, Phys. Rev. E **69**, 035601 (2004).
[6] I. V. Novikov and A. A. Maradudin, Phys. Rev. B **61**, 10484 (2000).
[7] D. E. P. Pile and D. K. Gramotnev, Opt. Lett. **30**, 1186 (2005).
[8] J. A. Dionne, L. A. Sweatlock, H. A. Atwater, and A. Polman, Phys. Rev. B **72**, 075405 (2005).
[9] H. T. Miyazaki and Y. Kurokawa, Phys. Rev. Lett. **96**, 097401 (2006).
[10] J. A. Dionne, L. A. Sweatlock, H. A. Atwater, and A. Polman, Phys. Rev. B **73**, 035407 (2006); Y. Kurokawa and H. T. Miyazaki, *ibid.* **75**, 035411 (2007).
[11] Z. Yu, G. Veronis, S. Fan, and M. L. Brongersma, Appl. Phys. Lett. **92**, 041117 (2008).
[12] T. W. Ebbesen, H. J. Lezec, H. F. Ghaemi, T. Thio, and P. A. Wolff, Nature (London) **391**, 667 (1998).
[13] S. Collin, F. Pardo, and J. Pelouard, Appl. Phys. Lett. **83**, 1521 (2003).

[14]C. Genet and T. W. Ebbesen, Nature (London) **445**, 39 (2007).
[15]M. M. Alkaisi, R. J. Blaikie, S. J. McNab, R. Cheung, and D. R. S. Cumming, Appl. Phys. Lett. **75**, 3560 (1999).
[16]H. Liu and P. Lalanne, Nature (London) **452**, 728 (2008).
[17]M. L. Brongersma, J. W. Hartman, and H. A. Atwater, Phys. Rev. B **62**, R16356 (2000).
[18]P. Lalanne and J. P. Hugonin, Nature (London) **2**, 551 (2006).
[19]J. O. Vasseur, A. Akjouj, L. Dobrzynski, B. Djafari-Rouhani, and H. El Boudouti, Surf. Sci. Rep. **54**, 1 (2004).