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Spatially resolved photonic transfer through mesoscopic heterowires

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We report spatially resolved observations of light wave propagation along high refraction index dielectric heterowires lying on a transparent substrate. The heterowires are made of linear chains of closely packed mesoscopic particles. The optical excitation of these heterowires is performed through channel waveguides featuring submicrometer transverse cross sections. Both numerical simulations and near-field optical images, recorded with a photon scanning tunneling microscope, agree to show that, at visible frequencies, tuning the periodicity of the heterowires controls the propagation length within a range of several micrometers.

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The scattering of light by periodic mesoscopic dielectric structures, whose sizes are of the same order of magnitude as the incident wavelength, has long been limited to theoretical studies [1]. Recently, the number of experimental works has grown rapidly, not only due to the expected applications in optical communication technologies, but also due to the development of adequate microfabrication techniques to produce relevant samples. Photonic band-gap crystals [2] form a specific class of mesoscopic dielectric structures. In such systems, an otherwise transparent reference medium is rendered opaque over some range of frequencies (and/or propagation directions) by modulating the three-dimensional dielectric function profile. This paper is devoted to a different point of view, which consists in dealing with periodic heterostructures to obtain transmission windows in the spectrum of an otherwise opaque reference system.

In the chosen point of view, the reference system has just to display an operational gap for a specific type of incoming wave. This is easier to realize as a complete gap for any kind of incident wave. As an example, an operational optical gap can be easily obtained by inserting a sufficiently thick layer of low refraction index material between two optically denser semi-infinite transparent media. Obviously, this system is an incomplete operational gap, since the transmission vanishes only when the angle of incidence is larger than the critical angle for total reflexion. If the thickness of the low index layer decreases to allow tunneling, the transmission does not drop down to zero anymore. However, this transmission level may be considered as the reference relative to which one measures the transmission efficiency of devices inserted in the low-index medium. Recently, numerical studies showed that heterowires, made of aligned mesoscopic dielectric particles featuring well-defined parameters, such as sizes and composition, can favor an optical resonant tunnel effect that achieves an enhanced optical transfer through such an operational gap [3,4]. Inspired by the two aforementioned works, an enhanced cross talk between two channel waveguides (modeling the incoming and outgoing high-index media of the operational gap) connected by a matrix of mesoscopic particles was reported [5]. On the basis of near-field calculations, a single heterowire with subwavelength transverse sizes, integrated in coplanar geometry and optically addressed by a channel microwaveguide (MWG), was found to be efficient for guiding visible light over distances of several micrometers [6].

Far-field measurements have already shown that a single heterostructure, obtained by drilling holes in a silicon channel waveguide, can switch off the transmission though the said waveguide [7]. To the best of our knowledge, no near-field observation of the light propagation through a *single* heterowire featuring submicrometer transverse sizes has been reported. For integrating heterowires in the design of optical submicrometer components, a direct measurement of the optical process occurring in these devices is highly desirable. The present paper reports the use of a photon scanning tunneling microscope (PSTM) [8] to obtain spatially resolved data demonstrating the photonic transfer through a *single* heterowire featuring submicrometer transverse sizes. Figure 1 shows a schematic view of our experimental setup. Each sample consists of a channel MWG aligned with an heterowire [Fig. 1(a)]. Both are made of high optical index materials (TiO_2) deposited on a glass substrate and are featuring submicrometer transverse sizes. The geometry of the heterowire is a row of closely packed parallelepipedic dielectric particles [Fig. 1(b)]. An index matching oil ensures the optical index uniformity between the glass substrate and the base of a 90° prism. A tightly focused He-Ne red laser beam ($\lambda = 633$ nm in vacuum, spot radius in the focal plane $= 5$ μm), incident through the prism, is totally reflected on the upper interface of the glass substrate. The focus is ad-

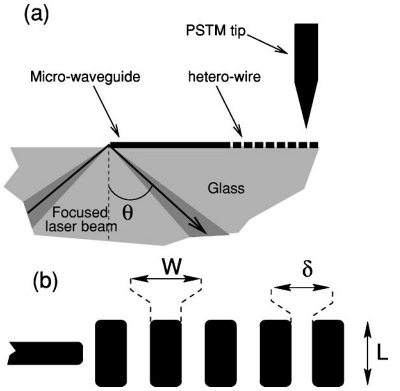

FIG. 1. (a) Schematic of the experimental setup. A PSTM probe is scanned over an heterowire which is addressed optically by a channel microwaveguide. (b) Geometry of the heterowires.

justed to shine on the entry end of the MWG. At the other end of the MWG, the light coupled into the MWG then excites the heterowire.

The PSTM images presented in this work were recorded using tips obtained by sharpening multimode optical fibers subsequently coated with 7 nm of chromium. This coating shields the radiative waves, which arise from the scattering by any small structure lying on a flat surface, in such a way that the said radiative waves do not contribute significantly to the detected signal. Since they do not sustain plasmon modes, the probes metallized with chromium detect a signal proportional to the electric near-field intensity [9–11]. Therefore, by scanning a chromium coated tip at constant height (less than 100 nm above the MWG-heterowire structure), the PSTM image maps the spatial distribution of the electric near-field intensity associated to the optical propagation along the MWG-heterowire structure.

When dealing with the interaction of light in ordered material displaying mesoscopic features, the structural properties of the unit cell (filling factor, refraction index, periodicity, etc.) determine the optical properties of the overall structure. In order to find out the geometrical parameters of an heterowire leading to an optimum guiding efficiency at an incident wavelength in vacuum $\lambda = 633$ nm, numerical computations were first performed using the Green dyadic method [12]. This method has proven to deliver outputs that are in agreement with the experimental PSTM images recorded above dielectric or metallic samples of arbitrary shapes [9–11]. To keep a reasonable computation time, the total length of the heterowires was limited to 6 μm. A previously tested beam model [6], featuring an incident focused beam with a submicrometer beam waist [see Fig. 2(a)], accounts for the local excitation of the heterowires. The dielectric function of TiO_2 was assumed to be constant ($\epsilon = 5.76$) over the whole range of visible frequencies. When the height of the particles is fixed, three geometrical parameters (W, L, δ) describe an heterowire [see Fig. 1(b)]. In order to avoid multiple computational situations, only the width W of the particles was varied while keeping constant both the length $L = 450$ nm and the interparticle distance $\delta = 150$ nm. Such values of L and δ were previously found to minimize the radiative losses along an heterowire excited by a MWG at $\lambda = 633$ nm [6]. Two values of W were then selected to demonstrate that changing the width of the particles switches the propagation along the heterowire on or off. Figure 2(b) displays the electric near-field intensity computed over the exit end of two heterowires whose widths are, respectively, $W = 350$ nm and $W = 200$ nm. These spectra attempt to model the signal that could be measured by locating the PSTM probe at the output of each heterowire and by sweeping the frequency of the incident light over the visible range. Both near-field spectra exhibit a broad transmission peak centered, respectively, around $\lambda = 740$ nm and $\lambda = 660$ nm. For an incident wavelength in vacuum $\lambda = 633$ nm, the near-field signal at the exit end of the heterowire, whose width W equals 200 nm, is expected by the computation to be about 20 times larger than the signal at the exit end of the one whose width W equals 350 nm. For this incident wavelength, the transmission through the heterowire made of the thinner particles ($W = 200$ nm) is much more efficient than through the other one ($W = 350$ nm).

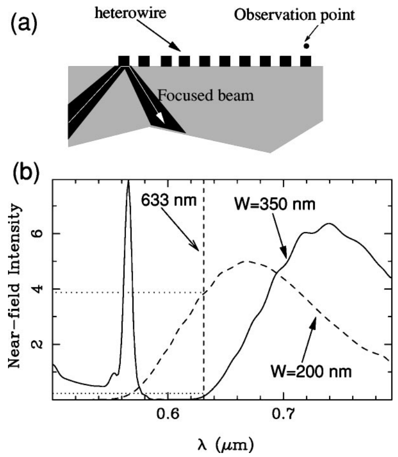

FIG. 2. (a) Numerical model for the computation of the near-field spectrum of an heterowire. (b) Theoretical near-field spectra computed for two different widths W of the particles in the heterowire.

To check this conclusion experimentally, two samples were microfabricated by electron beam lithography and reactive ion etching applied on a TiO_2 layer (thickness $= 150$ nm, refraction index $n = 2.4$) previously evaporated onto a BK7 glass substrate ($n = 1.5$). The two samples shown in Fig. 3 were obtained. Each sample consists of a 15-μm-long heterowire aligned along the longitudinal axis of a 30-μm-long channel MWG. The transverse dimensions and the distance between the particles are, respectively, equal to $L = 490 \pm 20$ nm and $\delta = 140 \pm 20$ nm for both samples. The two samples differ by the width W of the particles, which is found to be $W = 350 \pm 20$ nm for the first sample [Fig. 3(a)] and $W = 210 \pm 20$ nm for the second one [Fig. 3(b)].

Prior to the near-field imaging of the transmission through the heterowires, we first investigate the reference situation of a simple isolated channel MWG, which is not aligned with an heterowire to couple in. Figure 4(a) shows the near-field intensity I_{nf} recorded at constant height over the exit end of a 40-μm-long MWG excited, as detailed previously, by a fo-

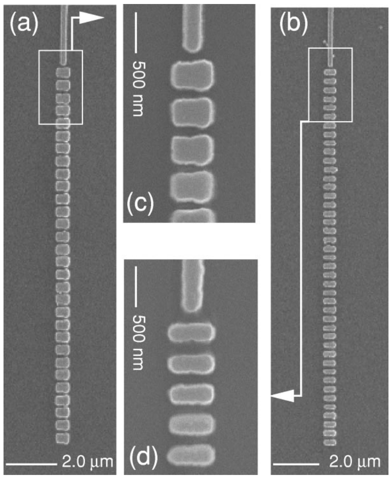

FIG. 3. Scanning electron microscope (SEM) images of two samples made of TiO_2. The width of the particles is found to be $W=350\pm20$ nm for sample (a) and $W=210\pm20$ nm for sample (b). (c) and (d) SEM images of the junction between the channel MWG, used for the optical addressing, and the heterowire on samples (a) and (b), respectively.

cused laser beam totally reflected on the substrate interface ($\theta_{inc}=50°$) and shining only the MWG entry end [6]. As it can be observed on the right part of Fig. 4(a), the large refraction index contrast between the MWG and the surrounding medium leads to a strong lateral confinement (along the Y direction) of the guided light. When reaching the MWG termination, the guided light is scattered and partly backreflected. A low contrast interference pattern with a periodicity of about 220 nm and visible along the MWG results from this backreflection while the scattering creates an intense and tightly confined spot with a radius of about 200 nm at half maximum [Fig. 4(b)]. This spot provides a submicrometer source of light which is used to address *locally* the heterowires when they are aligned with the MWG.

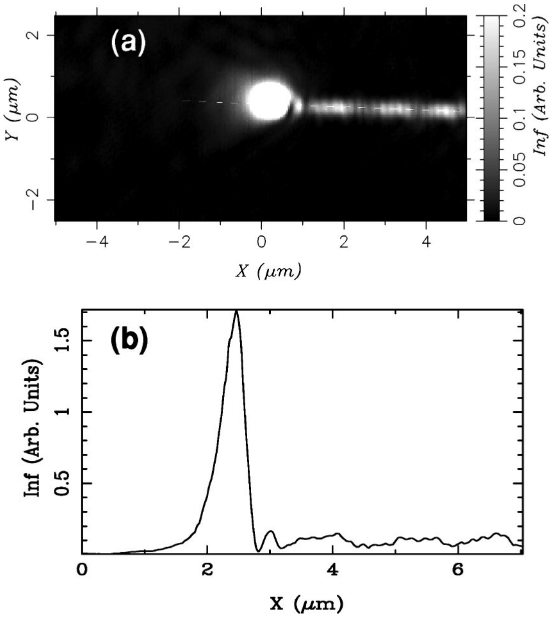

FIG. 4. (a) Constant height PSTM image recorded over the output of an isolated channel MWG (no heterowire aligned to couple in). (b) Crosscut along the white dashed line of the PSTM image. The MWG is excited by a focused He-Ne laser beam ($\lambda=633$ nm) as described in Fig. 1(a).

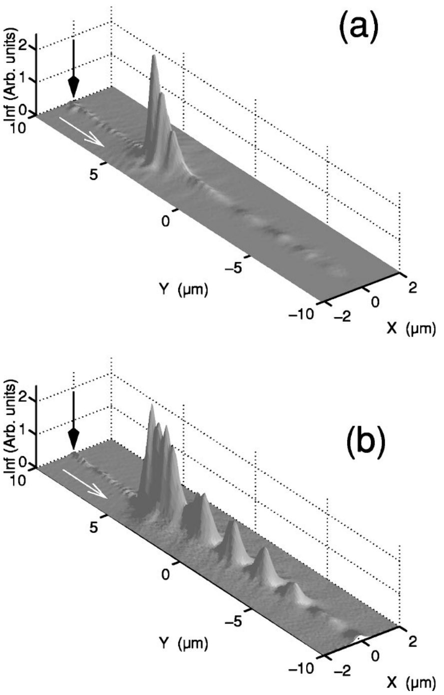

FIG. 5. PSTM images recorded over the two heterowires described in Fig. 3 and excited at $\lambda=633$ nm. (a) "Stopping" heterowire ($W=350$ nm). (b) Transmitting heterowire ($W=210$ nm). In (a) and (b), the black arrows show the location of the MWG and the white arrows show propagation direction of the incoming light.

We now discuss the PSTM images recorded over the two heterowires, $W=350$ nm [Fig. 5(a)] and $W=210$ nm [Fig. 5(b)], when they are excited by the field emerging from the exit end of the MWG. On the left part of these both three-dimensional views, one can identify (black arrow in Fig. 5) the weak and narrow near field of the mode of the MWG used for addressing optically each heterowire (propagation direction from the left to the right, along the white arrows in Fig. 5). The spot at MWG exit end, already observed on the reference situation (Fig. 4), appears on both images. However, while a dramatic damping of the near-field intensity occurs over the heterowire of Fig. 5(a), the near field extends over a much longer distance in Fig. 5(b). From this observation, we conclude that, in agreement with the computed near-field spectra [Fig. 2(b)], the propagation of an incident light with a frequency corresponding to a wavelength in vacuum $\lambda=633$ nm is much more efficient through the heterowire made with the thinner particles [$W=210$ nm, Fig. 5(b)]. The longitudinal cross cuts plotted in Fig. 6 allow a direct comparison of the transmission efficiency of both samples as a function of the distance X. The exponential decay of the envelope of each cross cut corresponds to a e^{-2} damping distance, which is less than 1.6 μm for the stopping heterowire and which is more than 7.5 μm for the transmitting one.

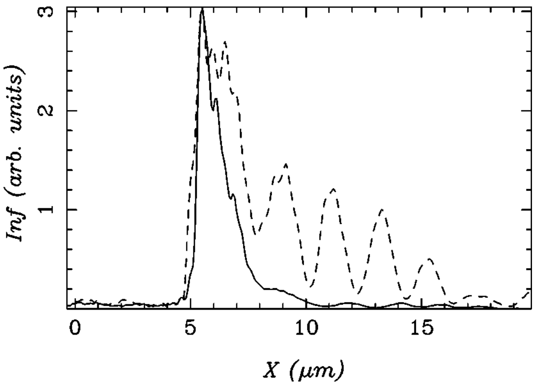

FIG. 6. Solid line (dashed line): Crosscuts of the PSTM images taken over the stopping (transmitting) heterowire.

Until now, we described the heterowires as chains of aligned particles. One could also consider that each heterowire is an homogeneous channel waveguide periodically interrupted by air gaps. From this point of view, it is interesting to notice that the transmitting heterowire corresponds to a waveguide, which is more perturbed than the stopping one. This indicates that the propagation along an heterowire relies less on the excitation of radiatives modes sustained by the heterowire as a whole but more on the overlap of the localized electromagnetic states sustained by each particle in the chain [13]. The better transmission observed in Fig. 5(b) can be attributed to a resonant optical tunnel effect [3]. Of course, the scattering by each particle of the heterowire leads to radiative losses, which damps the near-field intensity as a function of the propagation distance. However, these radiative losses do not explain the modulation of the near-field signal. Indeed, over the transmitting heterowire, this modulation (dashed line in Fig. 6) exhibits a pseudoperiod of about 2.0 μm, which does not match the actual periodicity of the heterowire. To explain this phenomenon, one might think about the recently reported quasi-interferences, with a period of several micrometers, which may occur inside a PSTM setup when probing the field of two mutually perpendicular modes of a homogeneous channel waveguide [14,15]. However, in our case, such a mechanism seems rather unrealistic since the local illumination emerging from the MWG probably mixes all polarizations.

To understand the origin of this modulation, let us suppose that the PSTM probe is located at a given position over the heterowire. In this situation, to reach the PSTM probe, the exciting field has to travel first along the heterowire such that the PSTM signal is proportional to the guiding efficiency of the piece of heterowire placed between the source (i.e., the MWG exit end) and the detector (i.e., the PSTM probe). The modulation of the PSTM signal could be related to a resonant transmission along subsets of the heterowire of specific lengths. In other words, the modulation observed on the experimental images is not an intrinsic property of the heterowire but is due to the presence of the PSTM tip. Indeed, when probing the transmitting heterowire, the PSTM tip opens an exit channel to the field propagating along the heterowire. This is consistent with the fact that a numerical study not including the PSTM tip finds that the near-field maps computed over a transmitting heterowire do not exhibit such a modulation [6].

In conclusion, we have used a PSTM to observe, in the direct space, the light propagation through heterowires made of rows of high refraction index mesoscopic particles. Numerical calculations determined the geometrical parameters of two sample heterowires featuring, respectively, low- and high-transmission efficiencies at a given wavelength. The subsequently microfabricated heterowires were addressed optically by a channel microwaveguide. The constant-height PSTM images show that the near-field intensity extends beyond 10 μm over the transmitting heterowire while the near-field intensity is severely damped over the stopping one. High-transmission-efficiency heterowires, exploiting the overlap of electromagnetic localized states, could be of practical interest to design miniaturized optical components.

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