Localization and Waveguiding of Surface Plasmon Polaritons in Random Nanostructures

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We propose to use channels in strongly scattering nonabsorbing random media for guiding electromagnetic waves, and demonstrate this concept using near-field microscopy of surface plasmon polaritons (SPP's) propagating along the gold film surface covered with randomly located scatterers. In the wavelength range of 725–765 nm, we observe complete inhibition of the SPP propagation inside the random structures composed of ~50-nm-wide gold bumps and their clusters with the density of 50 $\mu\mathrm{m}^{-2}$, as well as well-defined SPP guiding along corrugation-free 2- and 4-μm-wide channels.

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Interference in multiple scattering of light in nanostructured media may bring about a number of fascinating phenomena, of which strong (Anderson) localization in random media [1] and the photonic band gap (PBG) effect in periodic media [2] are probably the most prominent and intriguing ones. Considering the fact that a random (disordered) medium can be viewed as an antipode of a periodic (ordered) medium, these phenomena have surprisingly many features in common. Both are transport phenomena that result in the inhibition of light propagation (in the absence of absorption) manifesting itself as an exponential dependence of light transmission upon the medium thickness. The PBG effect occurs in a limited wavelength interval, when the periodicity of dielectric constant modulation in a medium matches half of the light wavelength (at least for some directions), leading essentially to Bragg reflection of light incident on the medium. Strong localization of light happens due to recurrent multiple scattering in random (nonabsorbing) media and is expected when the Ioffe-Regel criterion is satisfied, i.e., when $kl = 2\pi l/\lambda \leq 1$, where l is the (elastic) scattering mean free path and λ is the light wavelength. The product kl diverges in the limit of both short ($kl \sim 1/\lambda$) and long ($kl \sim \lambda^3$) wavelengths [3] ending in the same feature, viz., strong localization takes place in a limited wavelength interval. Furthermore, in both cases, variations of the medium dielectric constant should be large enough to realize sufficiently strong multiple scattering of light, i.e., both phenomena exhibit a threshold character with respect to the dielectric contrast. It should be noted that the threshold is noticeably higher for strong localization (since the interference effects are less effective in a random medium) making its direct observation quite a challenging task [4].

The quest for strong localization of light began a few years earlier [3] than that for the PBG effect [5]. In recent years, the latter, however, has attracted considerably more attention due to the possibility of efficient waveguiding along straight and sharply bent line defects in the PBG structures [6]. Combining a planar waveguide with a two-dimensional (2D) PBG structure containing appropriate line defects (to control the light propagation in the waveguide plane), one can realize highly integrated photonic circuits [7]. Various configurations of planar waveguides and PBG structures have been proposed and investigated [8], including a periodically corrugated metal surface whose corrugation modulates the propagation constant of surface electromagnetic waves, i.e., surface plasmon polaritons (SPP's) [9,10]. Given the similarities between the phenomenon of strong localization and the PBG effect, we realized that one should be able to employ channels and cavities in (nonabsorbing) strongly scattering random media for essentially the same purposes as those in the PBG structures. The fact that, in *two* dimensions, light is localized with *any* degree of disorder [1] makes the idea of using (quasi-)2D electromagnetic waves, e.g., planar waveguide modes or SPP's, in random structures especially appealing. One might suggest that the localization can be realized in a broader wavelength range than the PBG effect, since the former is not as directly governed by the geometrical characteristics of structured media as the latter. Furthermore, the absence of symmetry in random structures facilitates matching the modes propagating in differently oriented channels and, thereby, may reduce the associated bend loss.

In this Letter, we report what we believe to be the first observations of the inhibition of SPP penetration into randomly corrugated surface regions and SPP guiding along corrugation-free channels in these regions. SPP's propagate along a metal-dielectric interface and their electromagnetic fields, having the maximum at the interface, decay exponentially in the neighbor media [11]. SPP's can thereby be easily scattered by surface features and, e.g., localized by random surface roughness if the SPP scattering in the surface plane is sufficiently strong [12,13]. Here, instead of using natural surface roughness [13], we employ specially designed and fabricated random microscatterers to realize the SPP (strong) localization. The sample used in this work has been prepared by evaporating a 45-nm-thick gold film on a glass substrate and covering the film surface with $6 \times 18\ \mu\mathrm{m}^2$ rectangular areas filled with randomly located

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45-nm-high gold bumps. The latter has been achieved by exposing a resist layer coating the gold film to an electron beam at points whose surface coordinates (within these areas) have been randomly generated. The resist development has been followed by evaporation of a second gold film and liftoff, resulting in random ~50-nm-wide individual scatterers, arranged often in clusters. Areas with two different densities of scatterers, nominally $n_1 = 37.5\ \mu\text{m}^{-2}$ and $n_2 = 50\ \mu\text{m}^{-2}$, have been fabricated (Fig. 1). The final surface structure contained several areas having the same density and leaving 2- and 4-μm-wide channels free from scatterers in between.

The experimental setup was essentially the same as that used in our experiments with SPP band gap structures [10]. It consists of a scanning near-field optical microscope [14], in which the (near-field) radiation scattered by an uncoated sharp fiber tip into fiber modes is detected and an arrangement for SPP excitation in the Kretschmann configuration [11]. The p-polarized (electric field parallel to the plane of incidence) light beam from a Ti:Sapphire laser ($\lambda = 725$–850 nm, $P \sim 100$ mW) is weakly focused (spot size, ~300 μm) onto the sample attached with immersion oil to the base of a glass prism. The SPP excitation is recognized as a minimum in the angular dependence of the reflected light power. For a given angle, the SPP excitation remains close to optimum within ~20 nm of wavelength variation, but outside this interval the angle of the laser beam incidence has to be readjusted. The SPP excitation exhibited a well-pronounced resonance behavior with the average optical signal from the fiber being more than 10 times smaller when the incident angle was out of resonance. In the course of the experiments, we routinely verified the fact that the detected signal is primarily related to the total SPP field intensity distribution along the film surface by recording optical images at different fiber tip-surface distances [15]. The images retained the appearance up to the tip-surface distance of ~300 nm with the average signal decreasing exponentially (as expected) with the increase of the distance. For larger distances, the image appearance deteriorated and the signal decrease slowed down reaching a background value (> 10 times smaller than the signal at the surface) at the distance of ~1 μm. These features mean that the field components scattered out of the surface plane were relatively weak, i.e., that the SPP scattering was primarily confined to the surface plane. Finally, it should be noted that the images presented here (Figs. 2 and 5) are oriented in the way that the excited SPP propagates upwards in the vertical direction.

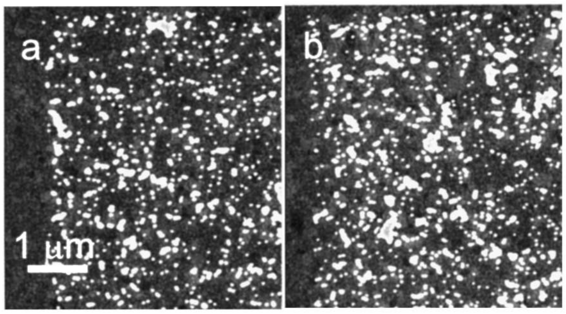

FIG. 1. Scanning electron microscope pictures of random structures of individual ~50-nm-wide gold bumps and clusters with a nominal density of (a) 37.5 and (b) 50 μm^{-2}.

The most pronounced effect of SPP guiding along the corrugation-free channels was observed in the wavelength range of 725–785 nm with the random structures having the largest density of n_2 of scatterers. The near-field optical image obtained at $\lambda \cong 738$ nm [Fig. 2(b)] shows a complete damping of the incident SPP inside the random structures and unhindered SPP propagation along the 4-μm-wide channel. The 2-μm-wide channel also supports the SPP propagation even though its excitation efficiency (by the incident plane SPP) is relatively small. The optical image cross section (averaged over a few lines) made at the distance of ~12 μm from the entrance side demonstrates well-confined mode intensity distributions for both channels (Fig. 3). Note that, if the propagation constant of an SPP channel mode is sufficiently different from that of the (plane) SPP, the channel mode cannot be excited with an incident laser beam adjusted to excite the SPP outside the random structure. In this case, it will decay as a result of absorption and radiative damping similarly to the SPP defect modes observed in periodic structures [10,16]. If the propagation constant turns out to be close to that of the SPP, one should expect the channel mode to maintain its amplitude while propagating in the region illuminated with the incident laser beam [16]. One can suggest that (in this wavelength range) the

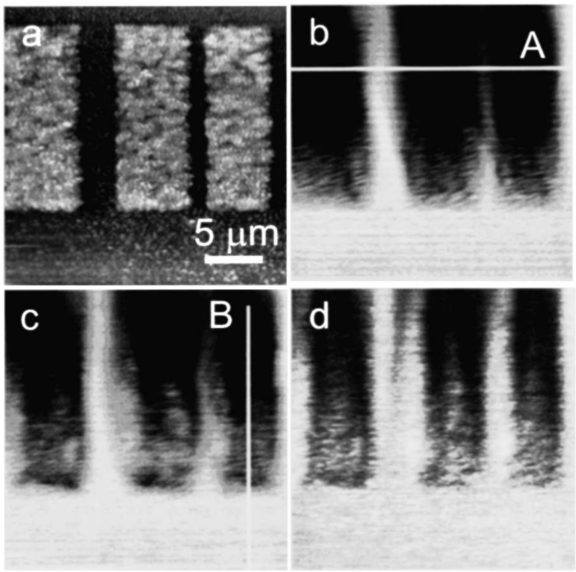

FIG. 2. Gray-scale (a) topographical and near-field optical images (25 × 25 μm^2) taken at $\lambda \cong$ (b) 738, (c) 785, and (d) 833 nm. Regions with random scatterers correspond to the structure shown in Fig. 1(b). Depth of the topographical image is 120 nm.

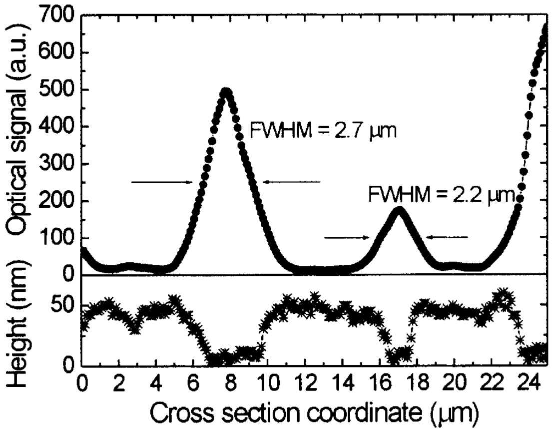

FIG. 3. Cross sections of the topographical [Fig. 2(a)] and near-field optical [Fig. 2(b)] images along the line marked *A* on the optical image.

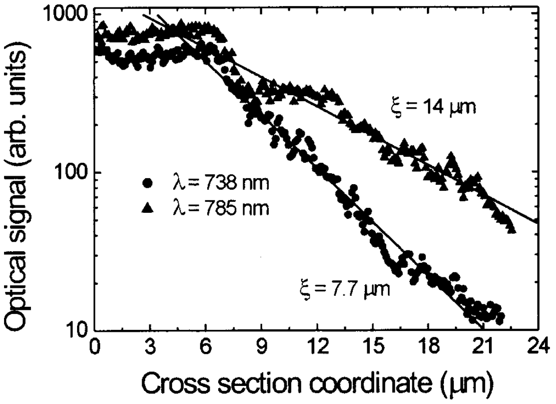

FIG. 4. Cross sections of the near-field optical images [Figs. 2(b) and 2(c)] averaged along 1-μm-wide stripes positioned as the line marked *B* on Fig. 2(c).

channel mode for the 2-μm-wide channel is close to the former case, while that for the 4-μm-wide channel is close to the latter. The SPP guiding along the channels and attenuation inside the random structure gradually deteriorated with the increase of the light wavelength [Fig. 2(c)], and the SPP damping became rather weak at $\lambda \cong 833$ nm [Fig. 2(d)]. Such a wavelength dependence can be accounted for by the fact that the scattering mean free path l increases with the wavelength because of the decrease (for subwavelength-sized scatterers) in the scattering cross section $\sigma(\lambda)$ [17] since $l \sim 1/n\sigma$. The increase of l leads, in turn, to an exponential increase of the penetration depth or localization length ξ, $\xi \sim l \exp(2\pi l/\lambda)$ [1], resulting thereby in the decrease of the SPP attenuation in the random structures.

The average cross sections of optical images (obtained at different wavelengths) made along the SPP propagation direction showed that the SPP intensity damping inside the random structures is very close to exponential, especially for short wavelengths (Fig. 4). Using the usual convention for the (average) intensity attenuation, $I(x) = I_0 \exp(-2x/\xi)$, and the exponential fitting of the cross sections (inside the random structures), we have found that the localization length changes only slightly around the value of ~ 7 μm within the wavelength range of 725–765 nm and increases for longer wavelengths. For example, $\xi \sim 25$ μm was determined for $\lambda \cong 850$ nm; however, this value should be considered as only an estimate since it exceeds the length (18 μm) of the random structure. Knowledge of the localization length allows one to estimate the scattering mean free path l and cross section σ (for the given density of scatterers) resulting in $l \sim 0.35$ μm and $\sigma \sim 60$ nm for $\xi \sim 7$ μm, $n_2 = 50$ μm^{-2}, and the light wavelength of 740 nm. It is interesting that the scattering cross section estimate is close to the actual width (~ 50 nm) of an individual scatterer, but it should be borne in mind that the cross section σ depends also on the height of the scatterer [17]. Note that the weak dependence $\xi(\lambda)$ around the wavelength of 740 nm indicates that, for the random structure in question, the corresponding value of ξ is close to minimum and, thereby, the wavelength $\lambda \cong 740$ nm is near the center of the localization gap.

Similar investigations carried out for the random structures with the density $n_1 = 0.75 n_2$ have shown considerably less pronounced effects of the SPP attenuation inside the random structures and the SPP guiding along the free channels (Fig. 5). For example, a localization length of ~ 10 μm and FWHM of ~ 3.2 μm of the mode intensity profile for the 4-μm-wide channel were estimated for $\lambda \cong 738$ nm. This deterioration is consistent with a strong dependence of the localization length on the density of scatterers: $\xi \sim (1/n\sigma)\exp(2\pi/n\sigma\lambda)$. For the same reason, the deterioration of the SPP guiding with the increase of the wavelength is more rapid for this structure than for that with larger density (cf. Figs. 2 and 5). We believe that, by fabricating random structures with larger densities of scatterers and/or larger scatterers (i.e., with larger scattering cross sections), one should be able not only to decrease further the localization length but also to increase the wavelength range in which the SPP guiding is well-pronounced.

In summary, we have suggested use of channels in strongly scattering (nonabsorbing) random media for guiding radiation and demonstrated this concept with SPP's propagating along a gold film surface covered with randomly located scatterers. In the wavelength range of 725–765 nm, we have directly observed complete inhibition of the SPP propagation inside the random structures composed of individual gold bumps (and their clusters) with the density of 50 μm^{-2}, as well as well-defined SPP guiding along corrugation-free 2- and 4-μm-wide channels. Note that, in our investigations of the SPP band gap in periodic structures [16], the efficient SPP guiding was observed in the wavelength range of 735–750 nm, which is considerably narrower than that above. We believe that the SPP localization length can be further decreased by increasing the scattering cross

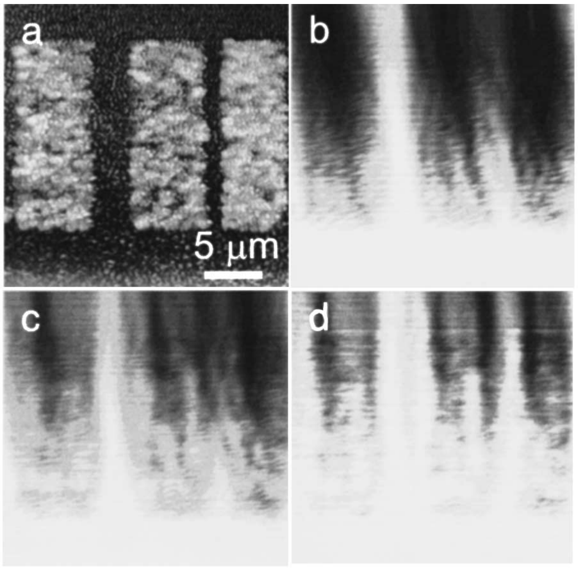

FIG. 5. Gray-scale (a) topographical and near-field optical images ($25 \times 25\ \mu m^2$) taken at $\lambda \cong$ (b) 738, (c) 763, and (d) 795 nm. Regions with random scatterers correspond to the structure shown in Fig. 1(a). Depth of the topographical image is 110 nm.

section of individual scatterers and/or their density allowing substantial improvement of the effects observed and exploration of other components (bends, splitters, cavities, etc.) similar to those suggested for 2D PBG structures [7,8]. It should be borne in mind that the reflection of light by random media is a complicated phenomenon that comprises diffuse reflection and coherent backscattering [1], implying that the waveguiding along channels in random media may exhibit nontrivial dispersion characteristics. This should result in a number of new exciting effects associated with guiding electromagnetic waves (e.g., SPP's) through random media.

Note added in proof.—Since the submission of our manuscript, we have conducted further investigations of the reported phenomena that support the above conclusions. Thus, using the procedure described above, we have fabricated a sample with areas containing 70-nm-high gold bumps (with a density of 75 μm^{-2}) placed randomly on a 55-nm-thick gold layer and 2-μm-wide straight and bent (10^0 and 20^0 bends with a bend radius of $\sim 15\ \mu m$) channels being free from scatterers. In the wavelength range of 713–795 nm, we have observed strong SPP attenuation with the localization length changing from 2.2 to 6 μm, respectively, and well-defined SPP guiding along the channels with the mode intensity profile having a FWHM of $\approx 1.7\ \mu m$ (Fig. 6). This constitutes a significant improvement of the SPP guiding characteristics (with respect to the reported ones) that we attribute to the increase in the scatterers' height and density. Finally, comparing straight and bent channels, we obtained a rather low level of additional bend loss (< 1 dB) in the wavelength range of 735–795 nm. This fact directly confirms that the SPP guiding along corrugation-free channels is related to the SPP scattering in the surface plane. A detailed report on these findings will be presented elsewhere.

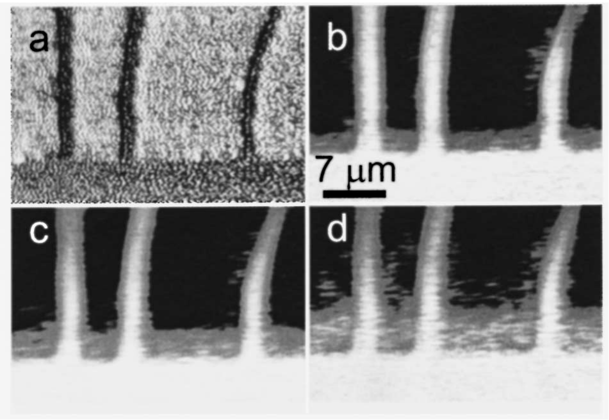

FIG. 6. Gray-scale (a) topographical optical images ($32 \times 22\ \mu m^2$) taken at $\lambda \cong$ (b) 713, (c) 750, and (d) 795 nm. Depth of the topographical image is 180 nm.

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[1] S. John, in *Scattering and Localization of Classical Waves in Random Media*, edited by P. Sheng (World Scientific, Singapore, 1990), p. 1.

[2] J. D. Joannopoulos, R. D. Meade, and J. N. Winn, *Photonic Crystals* (Princeton Press, Princeton, NJ, 1995).

[3] S. John, Phys. Rev. Lett. **53**, 2169 (1984).

[4] D. S. Wiersma, P. Bartolini, A. Lagendijk, and R. Righini, Nature (London) **390**, 671 (1997).

[5] E. Yablonovitch, Phys. Rev. Lett. **58**, 2059 (1987).

[6] A. Mekis *et al.*, Phys. Rev. Lett. **77**, 3787 (1996).

[7] T. F. Krauss and R. M. De La Rue, Prog. Quantum Electron. **23**, 51 (1999).

[8] *Photonic Crystal and Light Localization in the 21st Century*, edited by C. M. Soukoulis (Kluwer, Dordrecht, 2001).

[9] S. C. Kitson, W. L. Barnes, and J. R. Sambles, Phys. Rev. Lett. **77**, 2670 (1997).

[10] S. I. Bozhevolnyi *et al.*, Phys. Rev. Lett. **86**, 3008 (2001).

[11] H. Raether, *Surface Plasmons* (Springer-Verlag, Berlin, 1988).

[12] K. Arya, Z. B. Su, and J. L. Birman, Phys. Rev. Lett. **54**, 1559 (1985).

[13] S. I. Bozhevolnyi, Phys. Rev. B **54**, 8177 (1996).

[14] DME-DualScope^{TM}, Herlev, Denmark.

[15] S. I. Bozhevolnyi and V. Coello, Phys. Rev. B **58**, 10 899 (1998).

[16] S. I. Bozhevolnyi *et al.*, Opt. Lett. **26**, 734 (2001).

[17] A. V. Shchegrov, I. V. Novikov, and A. A. Maradudin, Phys. Rev. Lett. **78**, 4269 (1997).