Reducing crosstalk between nanowire-based hybrid plasmonic waveguides

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A B S T R A C T

Hybrid plasmonic waveguides based on a surface oxidized dielectric nanowire placed on a metal surface can facilitate simultaneously deep subwavelength mode confinement and large propagation length. Directional coupling based on such waveguides are theoretically investigated. Much lower crosstalk is noticed for such hybrid plasmonic waveguides compared to conventional waveguides based on bare dielectric nanowires. Some modifications, such as vertically placing the metal surfaces or using a metallic block between the nanowires, are studied which can further reduce the crosstalk between two waveguides. The proposed low crosstalk structures based on hybrid plasmonic waveguides can provide a simple platform for plasmonic integration which can at the same time easily interface with traditional photonic circuits.

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1. Introduction

Integrated photonic circuits have been widely believed to be a prospective candidate for replacing the electronic circuits as the next-generation on-chip information transmission technology. However, the integration capability of photonic devices is hindered by the diffraction limit of light. Plasmonic waveguides, which can overcome the diffraction limit and guide optical signals in a subwavelength scale, are expected to be one of the solutions for making high-density photonic integration possible. Recently, many types of plasmonic waveguides have been proposed, such as chain waveguides made of metallic nanoparticles [1,2], metallic wire or stripe waveguides [3,4], channel or wedge plasmonic waveguides [5–7], plasmonic slot waveguides [8], hybrid plasmonic waveguides [9–12], etc. For all these plasmonic waveguides, the trade-off between the propagation length and the mode confinement always exists. In general, with a subwavelength mode confinement, the propagation length for a plasmonic waveguide is as short as several micrometers [4,6,8] (while the propagation length of a Si waveguide is around several centimeters). Among them, the hybrid plasmonic (HP) waveguide [9,12] which confines the electromagnetic field in a narrow gap between a high index nanowire and a metallic substrate is found to be relatively superior: the waveguide has a relatively large propagation length (several-hundred micrometers) with a subwavelength mode confinement.

In this paper, we theoretically investigate the coupling and crosstalk characteristics between two parallel HP waveguides. Compared with the dielectric waveguides which have similar

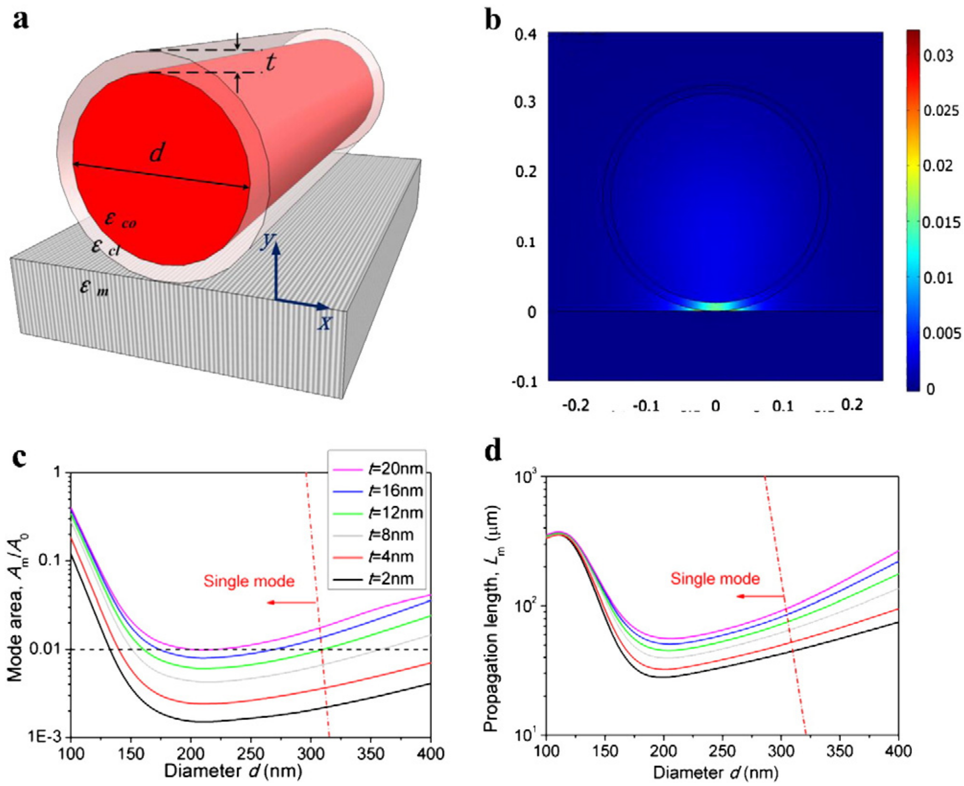

Fig. 1. (a) Schematic picture of the HP waveguide. A high index dielectric core (diameter d) with a low index cladding (thickness t) sits on a metallic substrate. (b) Electromagnetic energy density distribution for the HP waveguide with diameter $d = 200$ nm, thickness $t = 10$ nm (c) Normalized mode area A_m/A_0 and (d) propagation length L_m versus the diameters d and thicknesses t.

metal surface (Fig. 1b). The propagation length of the HP waveguide is defined as [9]

$$L_m = 1/(2\,\mathrm{Im}\{k(d,t)\}), \tag{1}$$

and the mode area is defined as [9]

$$A_m = \frac{W_m}{\max\{W(r)\}} = \frac{1}{\max\{W(r)\}}\iint_{-\infty}^{+\infty} W(r)d^2r, \tag{2}$$

where

$$W(r) = \frac{1}{2}\left(\frac{d(\varepsilon(r)\omega)}{d\omega}|E(r)|^2 + \mu_0|H(r)|^2\right) \tag{3}$$

is the electromagnetic energy density and W_m is the total electromagnetic energy. In the following discussions, the normalized mode area A_m/A_0 ($A_0 = \lambda^2/4$) is used.

The dependences of the normalized mode area A_m/A_0 and the propagation length L_m with respect to the core diameter at various cladding thicknesses are shown in Fig. 1c and d respectively. Inside the single mode region, there is only one fundamental quasi-TM mode supported by such a HP waveguide. It is interesting to notice that, for any thickness t in the range of 2–20 nm, the smallest propagation length and the best mode confinement always occur simultaneously at the diameter $d \approx 210$ nm. Take the thickness $t = 2$ nm as an example, the best mode confinement appears at the diameter $d = 210$ nm, with a normalized mode area $A_m/A_0 = 1.5 \times 10^{-3}$ and a propagation length $L_m = 28$ μm. For a larger diameter ($d > 210$ nm), the electromagnetic energy stays more in the core of the nanowire resulting in a larger mode area; while for a smaller diameter ($d < 210$ nm), the energy will spread into two side air corners. Although an excellent mode confinement is achieved, the propagation length is not very large compared with other kinds of plasmonic waveguides. To obtain a balance between the mode confinement and the propagation length, the HP waveguide with parameters $[d, t] = [300,12]$ nm is a good choice, at which the normalized mode area is $A_m/A_0 = 9.1 \times 10^{-3}$ (<0.01) and the propagation length is $L_m = 71$ μm.

3. Crosstalk between hybrid plasmonic waveguides

To study the crosstalk between the HP waveguides, we firstly consider the simplest condition that two nanowires is placed in parallel together on top of a metal substrate. The cross-section of the waveguides is shown in Fig. 2a. There are two eigenmodes for the coupled waveguides, a symmetric mode (Fig. 2b) and an anti-symmetric mode (Fig. 2c) [18–21].

Given the complex propagation constants $\beta_s + i\alpha_s$ and $\beta_a + i\alpha_a$ for the symmetric and anti-symmetric modes, the coupling length L_C can be computed as [21]

$$L_C = \frac{\pi}{\beta_s - \beta_a}. \tag{4}$$

Owing to the existence of propagation loss, even for two identical HP waveguides, a 100% coupling efficiency cannot be achieved. If the power is input into one HP waveguide, the maximum power obtainable in the other HP waveguide due to coupling is [22]

$$p_{\max} \cong \frac{\exp(-2\chi\arctan(1/\chi))}{1+\chi^2}, \chi = 2L_C/(\pi L_P) \tag{5}$$

where $L_P = 2/(\alpha_s + \alpha_s)$ is the mean attenuation length which is approximately twice of the propagation length for weak coupling. The length to achieve the maximum power transfer $p_{\max}$ is defined as $L_{\max}$.

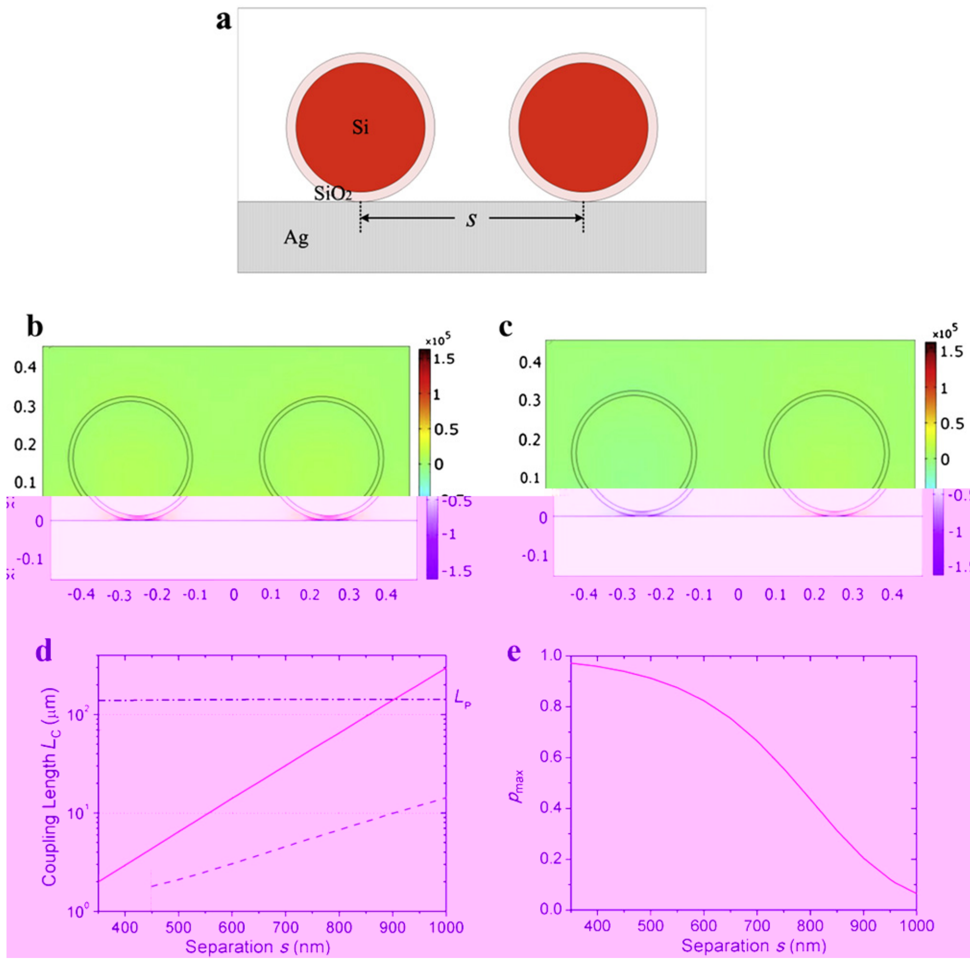

Fig. 2. (a) Cross-section of two parallel HP waveguides with a separation of s. (b)–(c) The E_y field distributions of the symmetric (b) and anti-symmetric (c) modes in a coupled HP waveguides system with $d=300$ nm, $t=12$ nm, and $s=500$ nm. (d) Coupling length L_C (red solid line) for the HP waveguides as a function of the separation s, compared with L_C for the pure dielectric waveguides composed by two bare nanowires with $d=300$ nm and $t=12$ nm (blue dashed line). The mean attenuation length L_P is plotted in black dot-dashed line. (e) Maximum power transfer p_{max} for the HP waveguides as a function of the separation s between two HP waveguides.

It is known that for the directional coupling, large coupling length L_C or small maximum power transfer p_{max} stands for low crosstalk. So what we will do is to design an optimal structure which can increase the coupling length L_C and decrease the maximum power transfer p_{max}.

In our simulations of the crosstalk and coupling, the parameters of the nanowires are set to be $[d, t]=[300,12]$ nm. The dependence of the coupling length L_C on the separation s between the centers of these two HP waveguides is shown in Fig. 2d (red solid line). As a comparison, the coupling length L_C for the coupling between two identical nanowires without the metallic substrate is also shown in Fig. 2d (blue dashed line). Obviously, with the same separation s, the coupling length L_C for the HP waveguides is much larger than the dielectric waveguides. This means that the HP waveguides have a much lower crosstalk than the dielectric waveguides. Take $s=1000$ nm for example, the coupling length L_C for the HP waveguides is about 20 times larger than that of the dielectric waveguides. For a shorter separation, such as $s=450$ nm, which is close to the cutoff of the anti-symmetry mode for a dielectric waveguides, the coupling length L_C for the HP waveguides is also about 2 times larger. The low crosstalk is due to the subwavelength mode confinement of the HP waveguides. Since most of the electromagnetic energy is highly confined in the gap, the mode overlap between the two HP waveguides is much weaker than that between the dielectric waveguides. The almost linear dependence of the coupling lengths on the waveguide separation is due to the fact that for a relatively weakly coupled waveguide pair the coupling length L_C increases with the separation s as $\sim\sqrt{s}\exp(\alpha s)$ [22], where $\alpha = \frac{2\pi}{\lambda}\sqrt{n_{eff}^2 - n_{clad}^2}$ is the decay constant and $n_{clad}=1$ (air) in our investigation. The constant slopes observed in Fig. 2d (in semi-log plot) are precisely determined by the decay constant α (while the effect of the factor $\sqrt{s}$ is much less significant). More specifically, our proposed HP waveguide has a $n_{eff}=2.05$ and that without a metallic substrate has a $n_{eff}=1.25$: their corresponding decay constants are 7.26 and 3.04, in accordance with Fig. 2d in that the slope for the HP waveguide system is much larger than that for the dielectric system.

The maximum power transfer p_{max} is another parameter to examine when one assesses the effect of crosstalk between two waveguides. As shown in Fig. 2e, for the above-mentioned two HP waveguides p_{max} decreases rapidly as the separation s increases. When $s=960$ nm, one has $p_{max}=0.1$, which means that at most 10% power can be transferred from one HP waveguide to the other. It should however be reminded that care should be taken for interpreting p_{max} since the parameter is also highly related to the propagation loss of the waveguide under consideration. A low value of p_{max} most often suggests a high propagation loss in the waveguide system. A cross-comparison of p_{max} is only meaningful if two systems are made of the same type of element waveguides. In the following discussions, we concentrate on crosstalk in systems based on the same HP waveguides illustrated in Fig. 1a. Therefore the maximum power transfer p_{max} can be considered as an effective parameter to compare the performances of these systems.

4. Further decrease crosstalk between hybrid plasmonic waveguides

Although HP waveguides lead to a much lower crosstalk than the corresponding dielectric waveguides, many improvements can be done to further decrease the crosstalk.

One approach is shown in Fig. 3a, where the metal surfaces are placed vertically. The substrate of a single HP waveguide is rotated by 90° compared to the structure in Fig. 2a. As shown in Fig. 2b, the electric field is well confined in the gap between the nanowires and the metallic slot in the vertical direction. Compared with the structure shown in Fig. 2, when the separation s between the centers of the two nanowires is the same, the distance between the gaps of the two HP waveguides increases by more than 300 nm. So a reduction of crosstalk can be expected for the HP waveguides with vertical substrates. In contrast to the normal HP waveguides in Fig. 2, the coupling length L_C for the HP waveguides with vertical substrates increases to be about 5 times larger (Fig. 3c) for any separation s. The almost identical slopes for the L_C–s curves found for the two types of waveguide systems are due to the fact that they are composed by essentially the same element waveguides, as we have discussed in the previous section. For a HP waveguide with a vertical substrate, its effective index is $n_{eff}=2.08$; therefore the decay constant is $\alpha=7.39$, which is very close to that for a normal HP waveguide with horizontal substrate ($\alpha=7.26$). We also deduced the maximum power transfer p_{max} for the system with vertical substrates as shown in Fig. 3d. Compared with the normal HP waveguide system (also shown in the same figure), now $p_{max}=0.1$ occurs at the separation $s=730$ nm which is much smaller than the separation $s=960$ nm for the normal HP waveguide system. The result indicates that the HP waveguides with vertical substrates can give rise to the same crosstalk as the normal HP waveguides within a much smaller volume.

Another straightforward way to reduce the crosstalk between two HP waveguides is to use a metallic block in between of the waveguides (Fig. 4a). It is obviously that both the width w and the height h of the slab will influence the coupling efficiency. Here, as the separation is set to a fixed value $s=500$ nm, the distance between the neighboring edges of the two HP waveguides is only 176 nm. Controlling the polarization to TM, there is only a fundamental TM mode existing for such HP waveguides (Fig. 4b). The variation of the corresponding coupling length L_C and the maximum power transfer p_{max} for different width w and height h is studied. The results are shown in Fig. 4c and d. With an increase in either the height h or the width w, the coupling length L_C increases and the maximum power transfer p_{max} decreases. For a slab with a width $w=150$ nm and a height $h=600$ nm, the coupling length is $L_C=3.3\times10^3$ μm which is ~500 times larger than that without the metallic slab ($L_C=6.5$ μm). With the decrease of the width w, the coupling length L_C also decreases. However, even when the slab has a width $w=50$ nm and a height $h=600$ nm, the coupling length is $L_C=86$ μm which is still more than 10 times larger than that without the metallic slab. More information can be obtained from the variation of the maximum power transfer p_{max} shown in Fig. 4d. For a slab with a height $h=600$ nm and a width $w=100$ nm the maximum power transfer is $p_{max}=0.01$, by which the crosstalk is much lower compared with that without the metallic slab ($p_{max}=0.9$). With the increase of the width w, the maximum power transfer p_{max} keeps decreasing to an even smaller value, at $<3\times10^{-4}$ when $w=150$ nm.

5. Conclusion

In conclusion, we have numerically investigated HP waveguides composed of a dielectric nanowire on a metal surface as well as crosstalk between such waveguides. Compared to the dielectric waveguides with a similar structure, the HP waveguides suffer from much lower crosstalk which is advantageous for realizing high-density integration. We also investigated different schemes to further reduce the crosstalk between the waveguides, such as placing the metallic substrates vertically and introducing a metallic block between the HP waveguides. The designed hybrid plasmonic waveguides can be readily fabricated with the current nanowire drawing technique, and should have potential applications in nanophotonics and integrated optical circuits. Moreover, even though only a specific HP waveguiding structure is considered here, our ways of reducing crosstalk should work for other HP waveguiding structures.

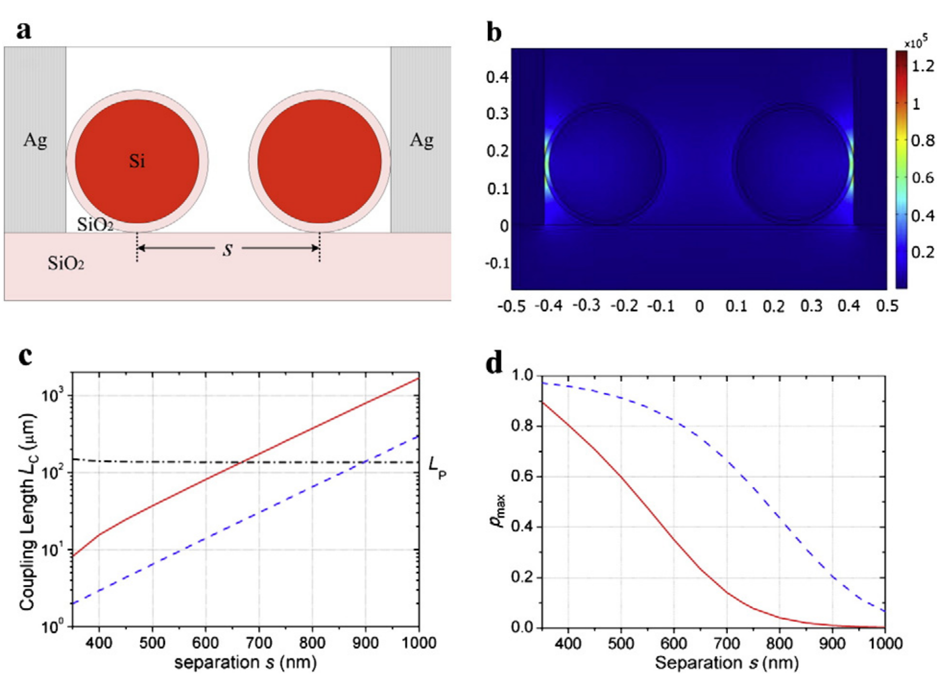

Fig. 3. (a) Cross-section of two parallel HP waveguides with vertical substrates and a separation s between two nanowires. (b) Distribution of E_x field for the symmetric mode of the coupled HP waveguides system with $d=300$ nm, $t=12$ nm, and $s=500$ nm. (c) Coupling length L_C (red solid line) for the metal-slot HP waveguides as a function of the separation s between two HP waveguides, compared with L_C for the normal HP waveguides (blue dashed line). The mean attenuation length L_P for the metal-slot HP waveguides is plotted in black dot-dashed line. (d) Maximum power transfer p_{max} for the metallic slotted HP waveguides as a function of the separation s between two HP waveguides.

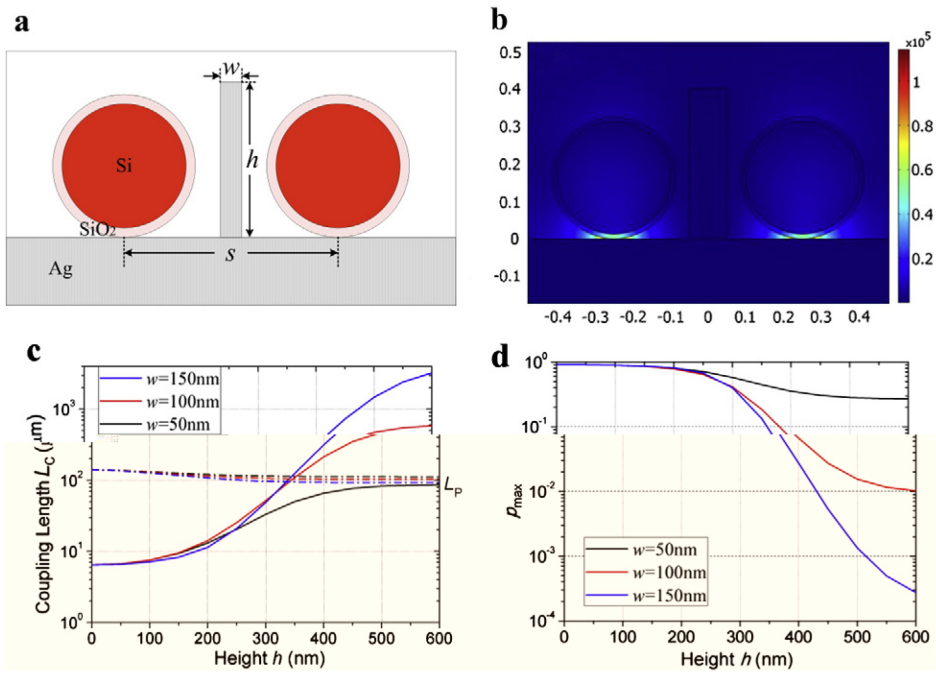

Fig. 4. (a) Cross-section of two parallel HP waveguides composed by placing a metallic block (with a width w and height h) between the nanowires with a separation s. (b) Distribution of E_y field for the symmetric mode of such HP waveguides with $d = 300$ nm, $t = 12$ nm, and $s = 500$ nm. (c) Coupling length L_C for such HP waveguides with the separation $s = 500$ nm and different width w as a function of the height h between the two HP waveguides. The mean attenuation length L_P is also plotted in dot-dashed line with the same color as L_C. (d) Maximum power transfer p_{max} for such HP waveguides with the separation $s = 500$ nm and different width w as a function of the height h between the two HP waveguides.

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References

[1] S.A. Maier, P.E. Barclay, T.J. Johnson, M.D. Friedman, O. Painter, Appl. Phys. Lett. 84 (2004) 3990.
[2] S.A. Maier, P.G. Kik, H.A. Atwater, S. Meltzer, E. Harel, B.E. Koel, A.A.G. Requicha, Nat. Mater. 2 (2003) 229.
[3] R. Charbonneau, N. Lahoud, G. Mattiussi, P. Berini, Opt. Express 13 (2005) 977.
[4] J. Takahara, S. Yamagishi, H. Taki, A. Morioto, T. Kabayashi, Opt. Lett. 22 (1997) 475.
[5] S.I. Bozhevolnyi, V.S. Volkov, E. Devaux, J.Y. Laluet, T.W. Ebbesen, Nature 440 (2006) 508.
[6] D.F.P. Pile, T. Ogawa, D.K. Gramotnev, T. Okamoto, M. Haraguchi, M. Fukui, S. Matsuo, Appl. Phys. Lett. 87 (2005) 061106.
[7] M. Yan, M. Qiu, J. Opt. Soc. Am. B 24 (2007) 2333.
[8] L. Chen, J. Shakya, M. Lipson, Opt. Lett. 31 (2006) 2133.
[9] R.F. Oulton, V.J. Sorger, D.A. Genov, D.F.P. Pile, X. Zhang, Nat. Photonics 2 (2008) 496.
[10] M. Fujli, J. Leuthold, W. Freude, IEEE Photon. Technol. Lett. 21 (2009) 362.
[11] R.F. Oulton, G. Bartal, D.F.P. Pile, X. Zhang, New J. Phys. 10 (2008) 105018.
[12] D. Dai, S. He, Opt. Express 17 (2009) 16646.
[13] P.B. Johnson, R.W. Christy, Phys. Rev. B 6 (1972) 4370.
[14] A.M. Morales, C.M. Lieber, Science 279 (1998) 208.
[15] D.D.D. Ma, C.S. Lee, F.C.K. Au, S.Y. Tong, S.T. Lee, Science 299 (2003) 1874.
[16] D. Shir, B.Z. Liu, A.M. Mohammad, K.K. Lew, S.E. Mohney, J. Vac. Sci. Technol. B 24 (2006) 1333.
[17] N. Fukata, T. Oshima, N. Okada, K. Murakami, T. Kizuka, T. Tsurui, S. Ito, J. Appl. Phys. 100 (2006) 024311.
[18] A. Hardy, W. Streifer, J. Lightwave Technol. LT-3 (1985) 1135.
[19] H.A. Haus, W.P. Huang, S. Kawakami, N.A. Whitaker, J. Lightwave Technol. LT-5 (1987) 16.
[20] W.P. Huang, J. Opt. Soc. Am. A 11 (1994) 963.
[21] A. Yariv, P. Yeh, Photonics: Optical Electronics in Modern Communications, Oxford University Press, 2007.
[22] G. Veronis, S. Fan, Opt. Express 16 (2008) 2129.