Rainbow trapping based on long-range plasmonic Bragg gratings at telecom frequencies*

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(Received 13 January 2013; revised manuscript received 14 March 2013)

The group velocity of long-range surface plasmon polaritons (LRSPPs) in a wide frequency bandwidth at infrared frequencies is significantly reduced by dielectric gratings of graded thickness on both sides of a thin metal film. This structure can reduce the propagation loss of slow surface plasmons in "rainbow trapping" systems based on plasmonic Bragg gratings. Compared with dielectric gratings of graded thickness on a single side of a metal film, the proposed structure is able to guide slow light with a much longer propagation distance for the same group index factor. Finite-difference time-domain simulation results show that slow LRSPPs with the group velocity of $c/14.5$ and the propagation distance of 10.4 μm are achieved in dielectric gratings of uniform thickness on both sides of a thin metal film at 1.62 μm.

Keywords: surface plasmon polaritons, slow light, photonic integrated circuits

PACS: 73.20.Mf, 42.25.Bs, 52.40.Db, 42.79.Gn **DOI:** 10.1088/1674-1056/22/7/077301

1. Introduction

Reducing the group velocity (υ_g) of light waves in optical materials at room temperature is an important issue because of a broad range of potential applications,[1] including enhanced light-matter interactions, optical buffers, and filters. However, most current slow-light systems can operate only at specific resonant frequencies, so it remains a great challenge to slow down υ_g in a wide frequency band. Metamaterials and plasmonics are cross-disciplinary fields that are emerging into the mainstream of many scientific areas.[2–9] Recently, "rainbow trapping" has been proposed as a scheme for localized storage of wide-band electromagnetic fields in metamaterials,[10] plasmonic grating structures,[11–16] and plasmonic heterostructures.[17–19] This demonstrates that these tapered waveguide structures are capable of localizing light waves of different frequencies at different positions. Quite recently, the "rainbow trapping" effect has been experimentally observed in adiabatically graded metallic gratings, where light of different wavelengths in the 500 nm–700 nm region is "trapped" at different positions along the grating.[16] However, metallic slow-light systems suffer from high propagation loss at optical wavelengths, which severely limits their use in practical applications.[20] It is therefore not surprising that overcoming loss restrictions in metamaterials has become one of the most important topics in nanophotonic research.[21] In this letter, we propose the use of dielectric gratings of graded thickness on both sides of a thin metal film to realize plasmonic "rainbow trapping" in the telecommunication domain. We reveal that the propagation loss of slow-light modes in the plasmonic grating structures can be significantly reduced as opposed to our previously proposed plasmonic grating structures.[13–15] As a result, this novel plasmonic structure is able to guide slow-light with a much larger group index ($n_g = c/\upsilon_g$, c is the speed of light) and longer propagation distance simultaneously.

2. Long-range plasmonic grating waveguides

We first compare four plasmonic models shown in Fig. 1, where models A and B are employed to construct the previously proposed plasmonic gratings for "rainbow trapping."[13–15] It is well-known that, in models C and D, symmetrical coupling of surface plasmon polariton (SPPs) on both surfaces of a thin metal supports the long-range SPP (LRSPP) mode with a much smaller propagation loss because less light energy will be located in the metal film.[22–26] In the calculation, the dielectric layer is Si ($n_d = 3.48$) while the metal film is silver, whose dielectric properties are gotten from the experimental parameters.[27] It is interesting to note that, for a fixed thickness of the Si layer, h, the propagation distances ($\lambda/4\pi n_{\mathrm{eff}}''$) of the LRSPP mode in models C and D, respectively, are 1 and 2 orders of magnitude greater than that of SPPs in models A and B for a given λ (see Fig. 1). And the corresponding n_{eff}' values of LRSPP mode in the former models are only slightly smaller than those of SPPs in the latter models. More interestingly, similar to model A, for a fixed wavelength, the corresponding n_{eff}' of the LRSPP mode in

*Project supported by the National Natural Science Foundation of China (Grant No. 11104093) and the Fundamental Research Funds for the Central Universities, China (Grant No. 2011QN041).

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model C increases monotonically with h. Therefore, instead of the plasmonic gratings reported in Refs. [13]–[15], we propose a long-range plasmonic Bragg grating (LRPBG) [see inset (a) of Fig. 2] to guide the slow LRSPP mode. The dispersion curve can be determined by incorporating the effective indices of LRSPP models in modes C and D into the secular equation for periodic structures.[13]

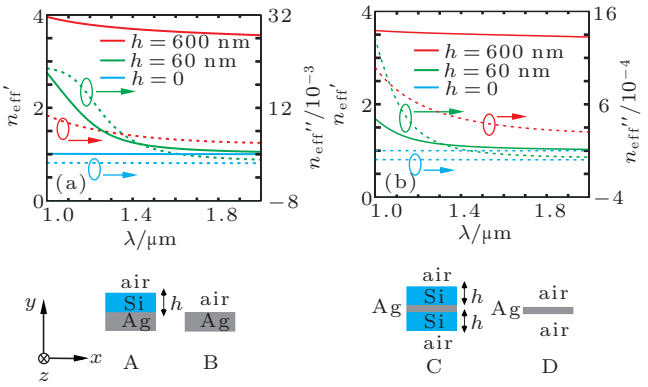


Fig. 1. (color online) (a) Dependence of the real part n_{eff}', and imaginary part n_{eff}'' of the effective refractive index of SPPs on wavelength λ for different grating thicknesses h. Model A: metal–dielectric–air model ($h \neq 0$), model B: metal–air model ($h = 0$). (b) Dependence of the real part n_{eff}', and imaginary part n_{eff}'' of the effective refractive index of the LRSPP mode on wavelength λ for different grating thicknesses, where the thickness of the silver film is 20 nm. Model C: air–dielectric–metal–dielectric–air model ($h \neq 0$), model D: air–metal–air model ($h = 0$).

Our calculation results show that the dispersion properties of the LRPBG can be tuned by systematically varying the grating thickness. Figure 2 shows the dispersion curves of the LRPBG with different grating thicknesses h. It can be seen that, with the increase of h, the cutoff frequency of the LRSPP mode in the LRPBG shifts from 300 THz ($\lambda = 1$ μm) with $h = 60$ nm to 161 THz ($\lambda = 1.86$ μm) with $h = 600$ nm, which is due to the fact that the n_{eff}' value of the LRSPP mode in model C increases as h increases. Given that the υ_g of a light wave will become very low as the light frequency approaches the cutoff frequency, we can infer that the υ_g of the LRSPP mode can be reduced significantly as incident light at $\lambda = 1$ μm and $\lambda = 1.86$ μm is coupled into the structure with $h = 60$ nm (or $h = 600$ nm).

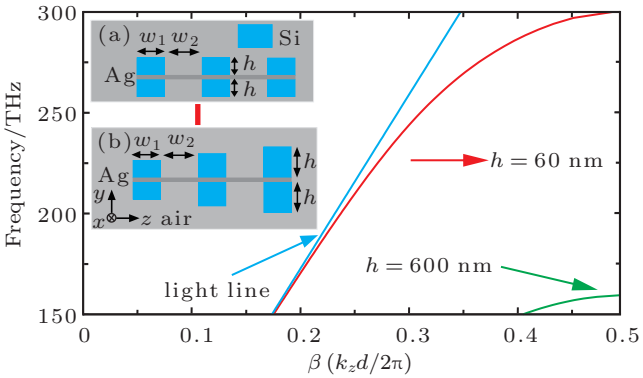


Fig. 2. (color online) Dispersion curves of a thin metallic film coated with a binary dielectric grating with thicknesses $h = 60$ nm and 600 nm, respectively. The widths of the Si and air layers are $w_1 = 100$ nm and $w_2 = 250$ nm, respectively. Inset (a) Schematic of the LRPBG. Inset (b) Schematic of the ALRPBG for LRSPP "rainbow trapping."

However, LRPBG can only slow down the υ_g of the LRSPP mode within a very narrow bandwidth near the cutoff frequency. To effectively enlarge the bandwidth of slow LRSPP mode, an adiabatic long-range plasmonic Bragg grating (ALRPBG) is proposed as shown in the inset (b) of Fig. 2, where the grating thickness h is linearly increased from 100 nm (left-hand side) to 670 nm (right-hand side) with steps of 5 nm, and the total length of the structure along z direction is approximately 40 μm. Since the grating thickness h is gradually increased along the propagation direction, the dispersion relations for ALRPBG vary monotonically with positions, indicating that the incident light of different wavelengths will be localized at different positions along the propagation direction.

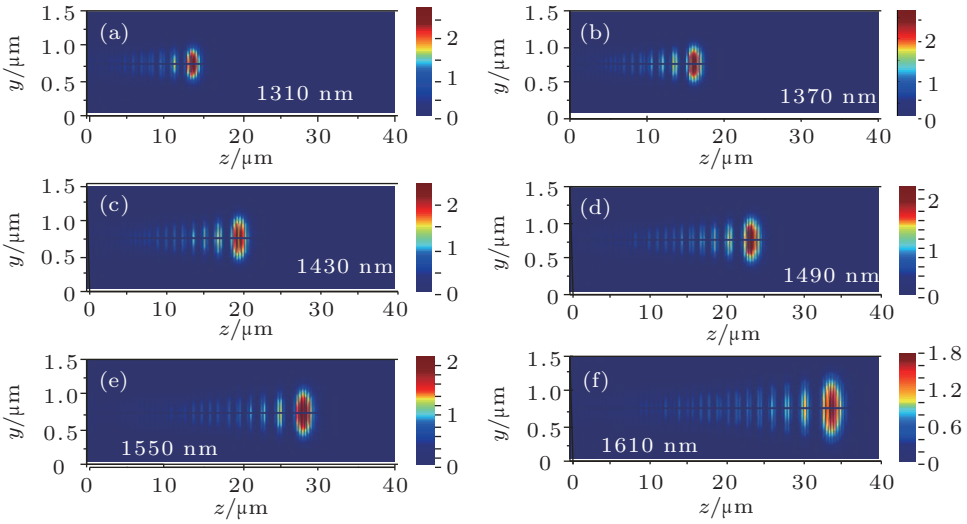


Fig. 3. (color online) FDTD simulated magnetic field intensity distributions ($|\boldsymbol{H}_x|^2$) of light waves through the graded plasmonic structure shown in the inset of Fig. 2 as the incident light is at (a) 1310 nm, (b) 1370 nm, (c) 1430 nm, (d) 1490 nm, (e) 1550 nm, and (f) 1610 nm, respectively. In the calculations, the grating thickness h increases linearly from 100 nm to 670 nm with steps of 5 nm, and the total length of the structure is approximately 40 μm.

The "rainbow trapping" concept described above can be confirmed by two-dimensional finite-difference-time-domain (FDTD) simulations. To effectively excite the LRSPP mode in the ALRPBG, a light source with a symmetrical distribution is set incident into the ALRPBG from the left-hand side. Figure 3 illustrates that light waves of different wavelengths in the infrared domain, i.e., 1310 nm, 1370 nm, 1430 nm, 1490 nm, 1550 nm, and 1610 nm, are localized at different positions along the grating structures. The corresponding grating thicknesses, where the six wavelengths are localized, are consistent with those predicted by the dispersion curves. We note that in a recent study chirped photonic crystal waveguides were also demonstrated to be capable of localizing light waves of different frequencies at different positions.[28,29]

3. Group velocity and propagation distance

To verify the slow-light characteristics of the LRPBG, the time evolution of LRSPP pulse propagation is theoretically demonstrated by FDTD simulation. A TM-polarized Gaussian pulse with pulse width (σ) of 103 fs and central wavelength 1.62 μm is incident into a LRPBG ($h = 540$ nm) from the left-hand side. Figure 4 shows the field intensity profiles of the LRSPP pulse at two positions (7 μm and 35 μm from the incident port, respectively). The time interval between the two positions is $\Delta t = 592.7$ fs and the n_g of LRSPP mode is $n_g = c\Delta t/d = 6.35$, where d (= 28 μm) is the distance between the two positions.

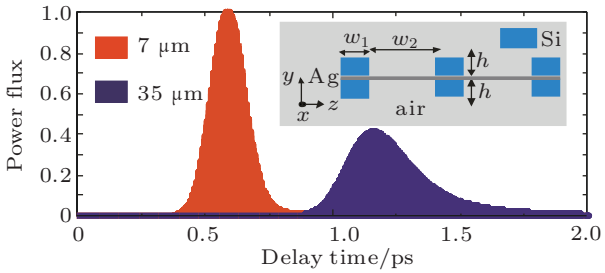


Fig. 4. (color online) Time evolution of the LRSPP wave packets at two spatial positions [7 μm (red solid line) and 35 μm (blue solid line) away from the incident port of an LRPBG with $h = 540$ nm]. In the calculations, the incident light is a TM-polarized Gaussian pulse with a pulse width (σ) of 103 fs and a 1.62-μm central wavelength. Inset shows the schematic of the LRPBG.

While the υ_g of the SPP mode in the previous plasmonic grating structures can be significantly reduced due to the high-index contrast between the neighboring dielectric layers, the propagation distance is limited to around 10 μm because a large portion of light energy is located in the metal film.[13–15] For practical applications, a large group-index factor and a long propagation distance must be satisfied simultaneously. We note that in a recent study, a plasmonic Bragg grating was found to be capable of supporting a usable propagation distance of slow SPP mode, however, the maximum υ_g is only approximately half of the light velocity in vacuum.[30] For our proposed LRPBG, on one hand, the high-index contrast between the neighboring dielectric layers will ensure a much smaller υ_g. On the other hand, since a much smaller portion of light energy will be located in the metal film, a larger propagation distance can be expected.

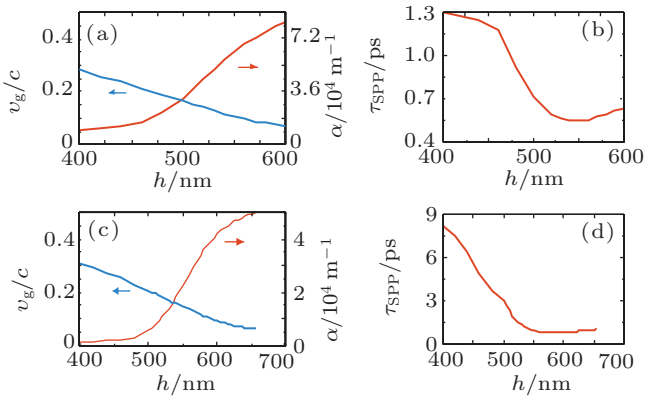


Fig. 5. (color online) Dependence of the attenuation coefficient α and group velocity υ_g (a) and lifetime τ_{SPP} (b) of SPP mode on grating thickness h for the structure shown in the inset of Fig. 2(a) in Ref. [5]. And dependence of the attenuation coefficient α and group velocity υ_g (c) and lifetime (d) of LRSPP mode on grating thickness h for the structure shown in the inset of Fig. 4. Here, the widths of the Si and air layers for the two structures are $w_1 = 100$ nm and $w_2 = 250$ nm. The excitation wavelength for both structures is 1620 nm.

Next, we will make a direct comparison between the previous plasmonic gratings with uniform dielectric gratings [shown in the inset of Fig. 2(a) in Ref. [5]] and LRPBG in terms of υ_g and propagation distance. For both structures, the propagation attenuation coefficient α (the propagation distance is defined as $L = 1/2\alpha$) can be extracted from FDTD simulated field distributions, while the υ_g can be indirectly obtained by recording the time evolution of a light pulse at different positions along the grating structures.[13,15] The two structures are compared at the same wavelength ($\lambda = 1.62$ μm). In order to have a meaningful comparison, we consider the same widths of the dielectric and air layers for both structures. In this case, the grating thicknesses associated with the cutoff frequency (185.2 THz) for both structures are different. For both structures, increasing the grating thickness h can monotonically reduce υ_g, but at the cost of the increased propagation loss [see Figs. 5(a) and 5(c)]. The υ_g reaches the minimum value as the grating thickness approaches the "cutoff thickness" associated with the cutoff frequency, where the propagation loss is increased to a maximum value. As the grating thickness is tuned away from the "cutoff thickness," the υ_g evolves gradually to the value of a straight SPP waveguide, where the propagation loss is minimal. However, the propagation loss of LRSPP mode in the LRPBG can be much smaller even with a larger n_g. For example, the n_g and the propagation distance of the LRSPP mode in the LRPBG with $h = 515$ nm

are 5.35 μm and 55.3 μm, respectively. In contrast, the corresponding n_g and propagation distance of SPP mode in the previous plasmonic gratings with $h = 480$ nm are 5.23 μm and 26.2 μm, respectively. As the grating thickness approaches the "cutoff thickness," where the υ_g is significantly reduced, the propagation loss of LRSPP mode in the LRPBG is still smaller than that in the latter one. The υ_g of the LRSPP mode in the LRPBG with $h = 635$ nm is significantly reduced to $c/14.5$, while the propagation distance is reduced to 10.4 μm. As for the previous plasmonic gratings with $h = 600$ nm, the corresponding υ_g and propagation distance are $c/14.3$ and 6.8 μm, respectively. Consequently, the corresponding photon lifetime (defined as $\tau_{SPP} = 1/\alpha\upsilon_g$) can be greatly enhanced in the LRPBG [see Figs. 5(b) and 5(d)].

4. Conclusion

In conclusion, we have proposed dielectric gratings of graded thickness on both sides of a thin metal film for realizing LRSPP "rainbow trapping" at telecom frequencies. Compared with the reported slow SPP mode obtained by dielectric gratings of graded thickness on a single side of a metal film, the propagation loss in such plasmonic grating structures can be made much smaller due to the fact that a smaller portion of the light energy is located in the metal film. Our simulation results demonstrate that the proposed structure is capable of guiding slow LRSPP mode with a much smaller υ_g and longer propagation distance. The present paper opens avenues for reducing propagation loss in broadband slow-light systems based on plasmonic grating structures, implying great potential applications in optical buffers, memories, data processors, optical filters, and sorters.

Acknowledgment

Chen Lin is grateful to Dr. Gan Qiao-Qiang for helpful discussions.

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