Mode-Selective Hybrid Plasmonic Bragg Grating Reflector

Liyang Lu, Fei Li, Mu Xu, Tao Wang, Jiayang Wu, Linjie Zhou, *Member, IEEE*, and Yikai Su, *Senior Member, IEEE*

***Abstract*— A mode-selective grating reflector based on a hybrid plasmonic waveguide, together with a two-to-one coupling structure, is proposed and analyzed. The grating structure is designed to reflect only the fundamental even mode existing in the hybrid plasmonic waveguide, and to pass through the fundamental odd mode at a 1550-nm wavelength with an extinction ratio of ∼16.7 dB. The simulated transmission spectra verify our analysis and the expected features of the mode-selective hybrid plasmonic Bragg grating.**

***Index Terms*— Bragg grating, even mode, hybrid plasmonic waveguide, odd mode.**

I. Introduction

As a solution to overcome diffraction limit in conventional dielectric waveguides and photonic devices, surface plasmon polaritons (SPPs) have been attracting tremendous attentions in the past years [1]. SPPs propagate along a dielectric-metal interface as a result of the interaction between collective oscillations of conducting electrons in metal and coupled electromagnetic (EM) waves. Utilizing their feature of confining the light in sub-wavelength scale, various SPP-based photonic devices with high integration density have recently been reported, including novel waveguides [2], directional couplers [3], and modulators [4].

Bragg grating reflectors play a central role in many photonic integrated devices, such as filters, vertical-cavity surface emitting lasers, micro-cavity resonators and light-emitting diodes [5], [6]. Plasmonic Bragg gratings with various waveguides, for instance insulator-metal-insulator (IMI) waveguide [7], metal-insulator-metal (MIM) waveguide [8], and hybrid plasmonic (HP) waveguide [9], have been investigated for their potential in replacing traditional dielectric gratings in highly integrated optical circuits.

In this letter, we propose a mode-selective Bragg grating reflector based on a HP waveguide with two low-index slots [2]. The structure is designed using effective index method (EIM). It shows different responses to even and odd optical modes in the waveguide. Different from the odd mode reflector based on the low-index cut off barrier in MIM waveguide [10], the proposed grating structure can be designed to reflect either the even mode or the odd mode. A 2-to-1 coupling structure is also proposed to stimulate the fundamental even mode and odd mode independently in the HP waveguide. Taking advantage of its different responses to different optical modes, this Bragg grating device can find its applications in many optical signal processing circuits such as filters, logical operations, format conversions, and tunable cavity resonators.

Manuscript received June 21, 2012; revised August 1, 2012; accepted August 6, 2012. Date of publication August 15, 2012; date of current version September 13, 2012. This work was supported in part by the National Science Foundation of China under Grant 61077052/61125504, in part by MoE Grant 20110073110012, and in part by the Science and Technology Commission of Shanghai Municipality under Grant 11530700400.

The authors are with the State Key Laboratory of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai 200240, China (e-mail: lu.liyang.1990@gmail.com; lifei2010@sjtu.edu.cn; xumu@sjtu.edu.cn; wangtao2007@sjtu.edu.cn; jiayangwu@sjtu.edu.cn; ljzhou@sjtu.edu.cn; yikaisu@sjtu.edu.cn).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2012.2213301

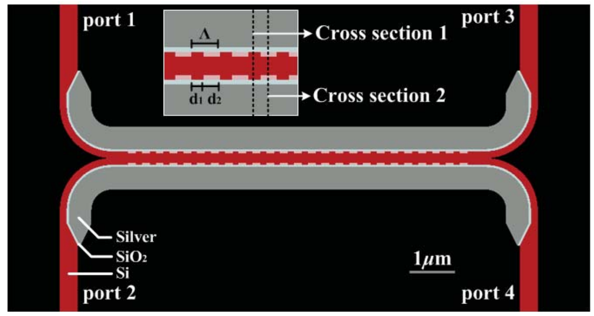

Fig. 1. Schematic diagram of the mode-selective hybrid plasmonic Bragg grating reflector (top view).

II. Device Structure

Fig. 1 shows the schematic diagram of the proposed mode-selective hybrid plasmonic Bragg grating reflector from top view, which is composed of a SiO_2-slot-width-modulated grating structure and two coupling structures that can convert the fundamental TE mode in two silicon waveguides into the hybrid plasmonic even mode and odd mode.

The Bragg grating is a periodic structure with a period of $\Lambda = d_1 + d_2$. d_1 and d_2 stand for the lengths of the waveguides with cross section 1 and 2, respectively. As depicted in Fig. 1 and 2(a), the cross section 1 comprises a rectangular silicon waveguide core with a width of W_{Si}, a height of H_{Si}, and a metal cladding with a thickness of W_{Ag} on a silicon-on-insulator (SOI) wafer. A SiO_2 layer with a width of W_{slot} is added between the sidewall of silicon core and the metal region. To reduce the absorption caused by the top metal layer, the thickness of the silica layer above the silicon core is increased to H_{SiO2} [2]. In cross section 2, the width of the SiO_2 slots is increased to W_{slot}', and the width of the silicon core is reduced to W_{Si}' accordingly. In the following simulations, the refractive indices for SiO_2

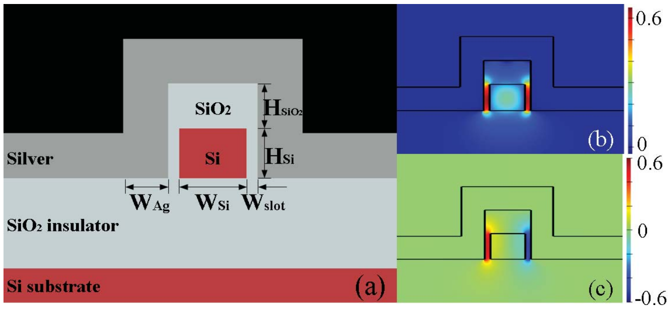

Fig. 2. (a) Cross section of the hybrid plasmonic waveguide. E_x distributions of (b) even mode and (c) odd mode in the cross section of a hybrid plasmonic waveguide with two SiO_2 slots.

and silicon around 1550-nm wavelength are assumed to be 1.445 and 3.475, respectively. The index for silver used in the simulations is given by the experimental data reported in [11]. Silver does not oxidize easily and has a relatively small plasmonic loss at the 1550-nm wavelength. Other stable metals with low losses could also be applied.

III. Simulation Results and Discussion

A. Fundamental Modes in Hybrid Plasmonic Waveguides

The HP waveguide shown in Fig. 2(a) with a silicon core width above 200 nm can support two fundamental optical modes with the intensity maxima located in the low-index silica slots between metal and silicon. One is an even mode and the other is an odd mode [4].

We use full-vectorial finite-difference algorithm (Mode Solutions) to numerically calculate the fundamental modes of the proposed waveguides at the 1550-nm wavelength. In order to support both the even and odd modes and get an appropriate modulation depth of the refractive indices, the geometrical dimensions are chosen as $W_{Si} = 300$ nm, $W_{Si}' = 200$ nm, $W_{slot} = 50$ nm, $W_{slot}' = 100$ nm, and $W_{Ag} = 200$ nm. $H_{Si} = 220$ nm is the thickness of the silicon layer on SOI wafer. To avoid the metal absorption of the top metal layer, H_{SiO2} is chosen to be 200 nm.

The simulated field distributions of the major component E_x for the fundamental even and odd modes are shown in Fig. 2(b) and (c). Different field distributions cause an obvious variance in the effective indices. For the waveguide with cross section 1, the simulated real parts of the effective indices for the even mode and the odd mode are 2.8431 and 1.9176, respectively.

With the increased width of the SiO_2 slots in cross section 2, more optical field exists in the low-index region for both the even mode and the odd mode, and the effective indices are thus reduced. The simulated effective index for the even mode is 2.2258 and that for the odd mode is 1.5038.

B. Coupling Structure

To couple light from the TE mode in silicon waveguide into the even and odd modes in the HP waveguide, a special 2-to-1 coupling structure is designed. As depicted in Fig. 1, a taper is used to convert the quasi-TE mode in single-mode silicon waveguide into a single-slot hybrid plasmonic mode. Two single-slot HP waveguides are combined together after the bends, and form a double-slot HP waveguide. Due to the

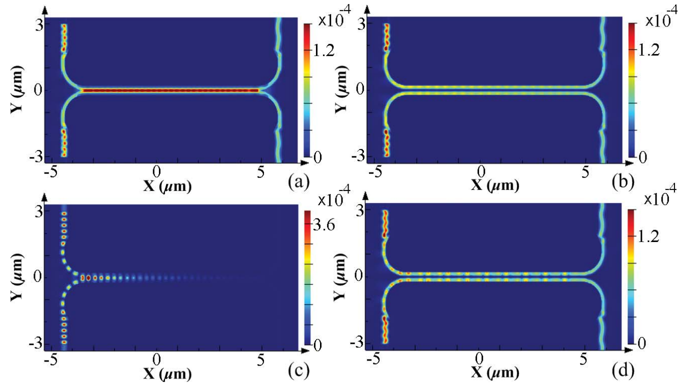

Fig. 3. H intensity distributions when inputs are (a) in-phase and (b) out-phase in the structure without gratings, and when inputs are (c) in-phase and (d) out-phase in the structure with gratings.

high field confinement feature of the HP waveguides, the bend radius can be reduced to ~1 μm with limited bending loss. At typical conditions, two in-phase optical signals with identical amplitudes input to port 1 and port 2 can form the even mode in the double-slot HP waveguide with a simulated coupling efficiency of ~86.2%, and two out-phase signals with the same amplitudes can stimulate the odd one with a coupling efficiency of ~84.8%. The distributions of magnetic fields under these two conditions in the structure without the gratings are illustrated in Fig. 3(a) and (b). If an arbitrary pair of signals are input to port 1 and port 2, their complex amplitudes can be expressed as $E_1 = E_S + E_A$ and $E_2 = E_S - E_A$, where E_S is the in-phase component stimulating the even mode and E_A is the out-phase component stimulating the odd mode.

C. HP Bragg Grating Reflector for the Even Mode

Using the EIM, a grating structure can be designed to reflect either the even mode or the odd mode around the 1550-nm wavelength, whose schematic diagram is shown in the inset in Fig. 1. In this letter, we present the reflector for the even mode.

The condition for Bragg reflection is given by [8]:

$$2\Lambda\widetilde{n}_{eff,\lambda_{B,1}} = m\lambda_{B,m} \tag{1}$$

where m is the order of the Bragg reflection, $\lambda_{B,m}$ represents the m-th order Bragg wavelength, and $\tilde{n}_{eff,\lambda B,1}$ is the averaged effective refractive index for the even mode at the first order Bragg wavelength, defined as:

$$\widetilde{n}_{eff,\lambda_{B,1}} = (d_1 n_{re,even,1} + d_2 n_{re,even,2})\big/(d_1 + d_2). \tag{2}$$

In (2), $n_{re,even,1}$ and $n_{re,even,2}$ stand for the real parts of the effective indices for even modes in cross section 1 and 2, respectively. According to the simulation results, the solution for (1) when $m = 1$ is $d_1 = \lambda_0/(4n_{re,even,1}) = 136$ nm and $d_2 = \lambda_0/(4n_{re,even,2}) = 174$ nm. Gratings with 25 periods are used in the simulations to demonstrate the performance of the design.

From Fig. 4(b) and (c), it is observed that the even mode at the first order Bragg wavelength of 1550 nm, is reflected by the Bragg grating and a standing wave is formed between the source and the grating reflector. However, the odd mode

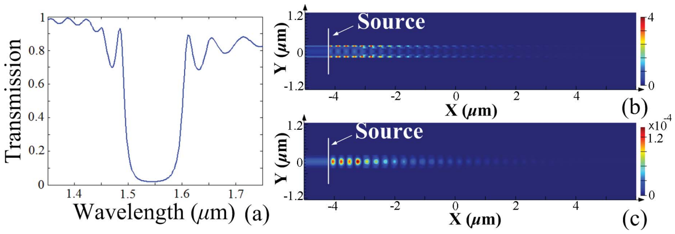

Fig. 4. (a) Transmission spectrum for the even mode. (b) E intensity and (c) H intensity distributions in the Bragg grating when input is even-symmetric at the 1550-nm wavelength.

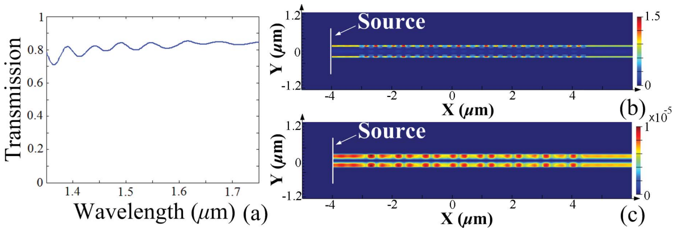

Fig. 5. (a) Transmission spectrum for the odd mode. (b) E intensity and (c) H intensity distributions in the Bragg grating when input is odd-symmetric at the 1550-nm wavelength.

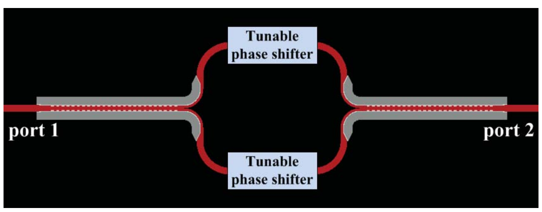

Fig. 6. Schematic diagram of the reflectance-tunable FP resonator.

at the same wavelength, as shown in Fig. 5(b) and (c), passes through the grating structure to the output port with almost no reflection.

The transmission spectra for the even and odd modes are plotted in Figs. 4(a) and 5(a), respectively. For the even mode, the transmission is below 5% between 1514-nm and 1578-nm wavelengths and reaches the minimum value of 1.79% near the 1550-nm wavelength. The odd optical mode, however, passes through the grating with a metal absorption loss below 18% around 1550 nm. The extinction ratio is calculated to be 16.7 dB. The simulated H intensity distributions for the overall structure with gratings are depicted in Fig. 3(c) and (d).

D. Proposed Application

The mode-selective hybrid plasmonic Bragg gratings can find its applications in many optical signal processing circuits such as filters, logical operations, and tunable cavity resonators. One possible application is a tunable Fabry-Perot (FP) resonator, where both the resonant wavelength and the amplitude of the filter can be tuned. As illustrated in Fig. 6, a phase-shifting device is added on each of the arms between two mode-selective Bragg gratings. The input signal to port 1 excites the even mode in the HP waveguide with the help of a taper. Two gratings act as the reflectors in the FP resonator. When the phase shifters are tuned with the same amount, the effective cavity length is changed and the resonant peak is shifted, as shown in Fig. 7(a). When the phase shifters are

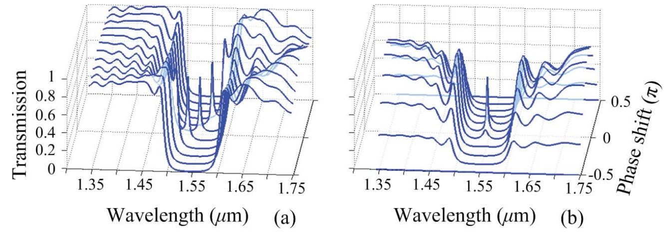

Fig. 7. Transmission spectrum of the FP resonator when the phase shifters are tuned. (a) With the same amount. (b) Oppositely.

tuned oppositely, a phase difference forms between the optical waves in two arms and a controlled portion of the signals is changed into out-phase component. Using the mode-selective feature of the gratings, only the in-phase component is mainly reflected while the out-phase component passes through them. The reflectance of two reflectors is thus changed in this FP resonator, and the resonant peak is suppressed from maxima, as shown in Fig. 7(b).

IV. Conclusion

In this letter, we propose and numerically analyze a mode-selective grating reflector based on a HP waveguide and a 2-to-1 coupling structure. Using the proposed 2-to-1 coupler, both even and odd modes can be independently excited in the HP waveguide with coupling efficiencies of ∼86.2% and ∼84.8%, respectively. The hybrid plasmonic grating structure is designed to reflect the even mode and to pass through the odd mode near the 1550-nm wavelength with an extinction ratio of about 16.7 dB.

With its different responses to the even mode and the odd mode, the mode-selective hybrid plasmonic Bragg gratings can be used to build new devices such as tunable cavity resonators.

References

[1] W. L. Barnes, A. Dereux, and T. W. Ebbesen, "Surface plasmon subwavelength optics," *Nature*, vol. 424, no. 6950, pp. 824–830, 2003.
[2] D. Dai and S. He, "Low-loss hybrid plasmonic waveguide with double low-index nano-slots," *Opt. Express*, vol. 18, no. 17, pp. 17958–17966, 2010.
[3] H. Zhao, X. Guang, and J. Huang, "Novel optical directional coupler based on surface plasmon polaritons," *Phys. E*, vol. 40, no. 10, pp. 3025–3029, Sep. 2008.
[4] X. Sun, L. Zhou, X. Li, Z. Hong, and J. Chen, "Design and analysis of a phase modulator based on a metal–polymer–silicon hybrid plasmonic waveguide," *Appl. Opt.*, vol. 50, no. 20, pp. 3428–3434, Jul. 2011.
[5] M. Rattier, *et al.*, "Toward ultrahigh-efficiency aluminum oxide micro-cavity light-emitting diodes: Guided mode extraction by photonic crystals," *IEEE J. Sel. Topics Quantum. Electron.*, vol. 8, no. 2, pp. 238–247, Mar./Apr. 2002.
[6] J. Wierer, D. Kellogg, and N. Holonyak, "Tunnel contact junction native-oxide aperture and mirror vertical-cavity surface-emitting lasers and resonant-cavity light-emitting diodes," *Appl. Phys. Lett.*, vol. 74, no. 7, pp. 926–928, 1999.
[7] J. Mu and W. Huang, "A low-loss surface plasmonic Bragg grating," *J. Lightw. Technol.*, vol. 27, no. 4, pp. 436–439, Feb. 15, 2009.
[8] J. Park, H. Kim, and B. Lee, "High order plasmonic Bragg reflection in the metal-insulator-metal waveguide Bragg grating," *Opt. Express*, vol. 16, no. 1, pp. 413–425, 2008.
[9] X. Yang, A. Ishikawa, X. Yin, and X. Zhang, "Hybrid photonic-plasmonic crystal nanocavities," *ACS Nano*, vol. 5, no. 4, pp. 2831–2838, 2011.
[10] J. Park, H. Kim, I.-M. Lee, S. Kim, J. Jung, and B. Lee, "Resonant tunneling of surface plasmon polariton in the plasmonic nano-cavity," *Opt. Express*, vol. 16, no. 21, pp. 16903–16915, 2008.
[11] P. B. Johnson and R. W. Christy, "Optical constants of the noble metals," *Phys. Rev. B*, vol. 6, no. 12, pp. 4370–4379, 1972.