Optics Communications 355 (2015) 591–595

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Discussion

An efficient hybrid plasmonic dichroic splitter based on subwavelength periodic metallic nanoslits

Chih-Chun Ho [a], Fan Lu [b], Kun Li [a], Dalin Liu [a], Anshi Xu [a],*

[a] *State Key Laboratory of Advanced Optical Communication Systems and Networks, School of Electronics Engineering and Computer Science, Peking University, Beijing 100871, China*
[b] *Beijing Institute of Spacecraft System Engineering, CAST, Beijing 100094, China*

ARTICLE INFO

Article history:
Received 10 March 2015
Received in revised form
6 May 2015
Accepted 21 May 2015
Available online 27 May 2015

Keywords:
Dichroic splitting
Hybrid plasmonic waveguides
Subwavelength metallic gratings

ABSTRACT

An efficient plasmonic dichroic splitter based on periodic metallic nanoslits milled in the metal–dielectric–Si hybrid plasmonic waveguide is proposed and investigated. The backside incident photons illuminated on the dichroic splitting structure are coupled and launched into the hybrid plasmonic modes propagating to the left- or right-side depending on the wavelength. Proof-of-principle demonstrations show that the good coupling and splitting performances with coupling efficiency 0.5 and high splitting ratios 26.4 dB at wavelength 1310 nm (right:left power contrast), and 0.46 and 21.7 dB at wavelength 1550 nm (left:right power contrast) are achieved, respectively. The operation principle is clarified and the performance is discussed.

1. Introduction

Surface plasmon polaritons (SPPs) are the electromagnetic waves trapped on metal–dielectric interfaces and coupled to propagating free electron oscillations in the metals, which are considered as promising candidates for highly integrated optical circuits due to the manipulation of light on submicrometer scales and the significant overcoming of classical diffraction [1]. So far a large diversity of plasmonic microstructures have been proposed and demonstrated, which raise an intriguing prospect of realizing high speed information processing on chip in future optical communication [2,3]. However, before achieving the full potential of surface plasmon technology, the issues of coupling SPPs from freely propagating light and controlling the direction of propagation of the generated SPPs need to be solved for the development of plasmonic devices and systems [4]. Poor directionality frequently represents a substantial source of noise and reduces efficiency. This has led to the development of various types of schemes that unidirectionally couple SPPs, such as a single nanoslit with Bragg reflection [5] or phase-interference [6], the aperiodic groove arrays [7], and the compact nano-antenna [8].

However, most of these plasmonic couplers were designed to excite SPPs on the traditional metal–air waveguide. As a result, the propagation distance is usually deteriorated because of the large transmission loss of SPPs in such metal–air interface.

Hybrid plasmonic modes have integrated the characteristics of both metal–insulator–metal (MIM) waveguides and dielectric waveguides. Therefore, compared to the conventional SPP modes, hybrid plasmonic modes can achieve a better trade-off between the propagation length and the field confinement, which have been recognized as a promising method to improve transmission loss and to solve modes confinement problems in the new plasmonic functionalities [9,10,12,13]. Since hybrid plasmonic waveguide has shown great potential for future applications, the unidirectional coupling of light into hybrid plasmonic waveguides becomes an instant research topic. An efficient hybrid plasmonic coupling mechanism has been proposed and theoretically demonstrated using the semi-analytical coupled-mode model [14]. Moreover, the bidrectional hybrid plasmonic splitters are much harder to be achieved and there is little further research on this.

During recent years, bidirectional plasmonic dichroic splitters have gained increasing research interest [15–17], which are capable of coupling and splitting SPPs of two different wavelengths into opposite directions. Especially for the applications such as bistable switching [19], wavelength demultiplexing [20], and plasmonic photon sorting [21], plasmonic dichroic splitters coupling specific wavelengths into predetermined channels will play an important role in photonic integrated circuits. Liu et al. [16] presented a submicron plasmonic dichroic splitter based on a pair of asymmetric grooves. The dichroic splitting response was successfully demonstrated with a splitting ratio of 3:1 at shorter wavelengths reversing to 1:2 at longer wavelengths. Zhang et al.

---

* Corresponding author.
E-mail address: lyrxas@pku.edu.cn (A. Xu).

http://dx.doi.org/10.1016/j.optcom.2015.05.046

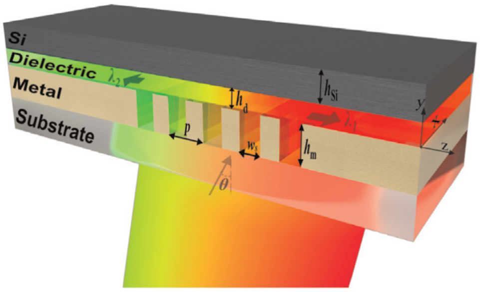

Fig. 1. Schematic of the proposed hybrid plasmonic dichroic splitter. The structure is composed of N periodic nanoslits of width w and period p milled in the metallic surface of the Si–dielectric–metal hybrid plasmonic waveguide.

[17] demonstrated a remarkable composite cavity structure to split SPPs of two different wavelengths into opposite directions with high splitting ratios of 1:24 and 23:1 at splitting wavelengths of 767 nm and 847 nm. Besides, Li et al. [18] proposed a metallic cascaded-grating structure to achieve the plasmonic dichroic splitting with high splitting ratio (43.0 dB and 35.7 dB at wavelengths 1310 nm and 1550 nm, respectively), but the coupling efficiency is also weak and the propagation loss of the excited propagating modes is large.

Moreover, the splitting performance and the propagation length of excited plasmonic modes of these structures need to be further improved to meet future plasmonic applications. As a result, the ability to couple and split dichroic plasmonic modes into opposite directions with a high efficiency and splitting ratio, and much longer propagation length, although highly desirable, still remains a challenge.

In this paper, we propose a hybrid plasmonic dichroic coupling and splitting structure based on periodic nanoslits milled in the hybrid plasmonic waveguide, as shown in Fig. 1. The backside incident TM-polarized photons on the structure are coupled and launched into the hybrid plasmonic modes propagating to the left- or right-side depending on the wavelength. This ability of efficient coupling and sorting photons dependent on wavelengths relies on the grating Bragg matching condition and the strong mode confinement of hybrid plasmonic waveguide. The proposed structure offers better performance with high splitting ratios of 26.4 dB and 21.7 dB, coupling efficiency of 0.5 and 0.46, and longer propagation length 104 μm and 84 μm at the splitting wavelengths of 1310 nm and 1550 nm, respectively. Its operation principle and the performance will be investigated and discussed.

2. Theory and operation principle

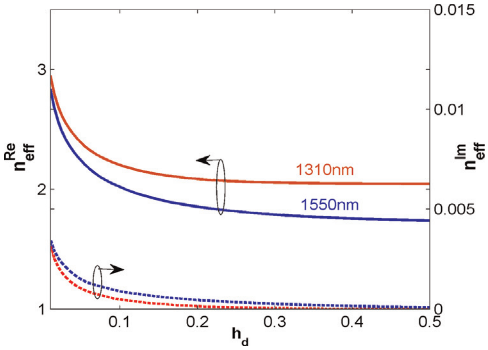

Fig. 2. Calculated dependence of the real and imaginary parts of the effective refractive index n_{eff} of the hybrid plasmonic modes on the dielectric-film thickness h_{d} for a given thickness of the Si-film h_{Si} = 200 nm.

Fig. 1 schematically shows the proposed hybrid plasmonic dichroic splitting structure illuminated by TM-polarized plane waves (magnetic field parallel to x-axis). An optically thick metal film of thickness h_{m} is deposited onto a glass substrate (n_{sub} = 1.46), and N periodic subwavelength nanoslits are milled in the film. Then a low-index dielectric film of thickness h_{d} is added onto the metal film as well as filling the slits. At last, a Si film with thickness h_{Si} is added onto the top of the sandwiched dielectric film, where the Si–dielectric–metal structure constitutes the hybrid plasmonic waveguide. Obliquely incident photons are converted into hybrid plasmons propagating to the left- or right-side depending on the incident wavelength. Note that backside illumination used here eliminates the possible significant noise introduced by the incident light. Without loss of generality, silver with frequency-dependent permittivities tabulated in [22] is used as the metal. The refractive index of dielectric film is assumed to be n_{d} = 1.46, which could be the common low-index dielectric such as $\mathrm{SiO_2}$, or PMMA.

According to the grating theory, the period of the metallic slits to couple the incident light and excite the propagating modes relies on the Bragg phase matching condition,

$$k_{\mathrm{in}}\sin\theta + \mathrm{m}k_{\mathrm{g}} = \pm\, k_0\,\mathrm{Re}(n_{\mathrm{eff}}), \tag{1}$$

where $k_{\mathrm{in}} = k_0 n_{\mathrm{sub}} = 2\pi n_{\mathrm{sub}}/\lambda$ is the incident wave vector, $k_{\mathrm{g}} = 2\pi/p$ is the reciprocal lattice vector of the grating, $n_{\mathrm{eff}} = \mathrm{Re}(n_{\mathrm{eff}}) + \mathrm{Im}(n_{\mathrm{eff}})i$ is the effective refractive index of the propagating mode in the hybrid plasmonic waveguide, θ is the incident angle, and m is the diffraction order. For the different incident wavelengths, Eq. (1) could be further written as

$$n_{\mathrm{sub}}\sin\theta + \mathrm{m}_1\lambda_1/p = \pm\,\mathrm{Re}(n_{\mathrm{eff}}^{\lambda 1}), \tag{2a}$$

$$n_{\mathrm{sub}}\sin\theta + \mathrm{m}_2\lambda_2/p = \pm\,\mathrm{Re}(n_{\mathrm{eff}}^{\lambda 2}). \tag{2b}$$

Fig. 2 presents the variation of the mode effective index n_{eff} with thickness h_{d} of the dielectric film for different incident wavelengths (1310 nm and 1550 nm), where the thickness of the Si-film is set as h_{Si} = 200 nm. The n_{eff} is calculated by the fully vectorial aperiodic Fourier modal method (a-FMM) [11]. Here, the thickness of dielectric-film is set to be h_{d} = 50 nm, which could facilitate the design requirements and realize the strong confinement of hybrid mode [12]. Then the corresponding $\mathrm{Re}(n_{\mathrm{eff}}^{\lambda 1})$ = 2.385 for 1310 nm and $\mathrm{Re}(n_{\mathrm{eff}}^{\lambda 2})$ = 2.236 for 1550 nm are obtained, respectively.

The wave-vector diagram, an intuitive representation of Eq. (2) for our structure is shown in Fig. 3. As designed, the incident light of wavelength λ_1 = 1310 nm is coupled into right-going hybrid plasmonic mode, where we set $m = +1$ for λ_1 = 1310 nm in Eq. (2). Similarly, the incident wavelength λ_2 = 1550 nm is coupled into left-going mode, where we set $m = -1$ for λ_2 = 1550 nm in Eq. (2). Thus Eq. (2) is deduced into

$$n_{\mathrm{sub}}\sin\theta + \lambda_1/p = \mathrm{Re}(n_{\mathrm{eff}}^{\lambda 1}), \tag{3a}$$

$$n_{\mathrm{sub}}\sin\theta - \lambda_2/p = -\,\mathrm{Re}(n_{\mathrm{eff}}^{\lambda 2}). \tag{3b}$$

It is clear that the hybrid plasmonic modes at different wavelengths

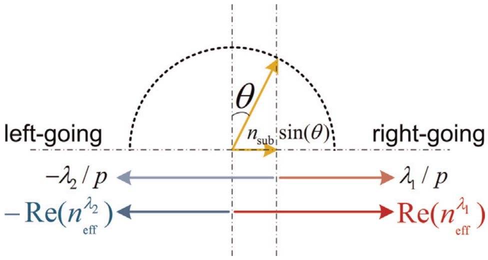

Fig. 3. Wave-vector matching diagram for the hybrid plasmonic dichroic splitting.