# Plasmonic wavelength splitter based on a large-area dielectric grating and white light illumination

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An optical process by which transmission wavelengths can be divided selectively by changing a resonance condition of surface plasmons (SPs) is demonstrated. When white light is incident to an SP resonance substrate with a dielectric grating, SP waves are excited at resonance and transmitted into the air via diffraction by a large-area grating pattern fabricated by nanoimprint lithography. While only a limited range of certain wavelengths is allowed to transmit, the peak transmission wavelength can be tuned continuously in the visible band. We also show that multiple wavelengths are transmitted into different directions simultaneously by using a wedge-shaped white light. 

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Surface plasmon (SP) waves can be described as collective electron oscillations occurring at an interface of metal and dielectric [1]. When transverse magnetic (TM)-polarized light satisfies a resonance condition, the electromagnetic field generated by SP waves is strongly enhanced and confined in the vicinity of the metal surface as a nonradiative evanescent field. The ability to concentrate the electromagnetic energy on the localized nanoscale domain, often in combination with a metallic nanostructure, may offer unique opportunities in a variety of technology developments, such as near-field microscopy [2], fluorescence detection [3], photovoltaic solar cells [4], and plasmon-assisted excitation schemes [5]. More recently, serious efforts have been also made to achieve enhanced field intensity or efficient light transmission through plasmonic waveguides or plasmonic nanoantennas [6–10].

Contrary to those approaches for optical manipulation, efficient outcoupling of SP waves to radiation modes by dielectric diffraction gratings was demonstrated based on an attenuated total reflection configuration [11], and since then several applications such as the optical biosensor and holographic display have been introduced [12,13]. However, the potential for a wavelength selection and division device, a crucial functionality for an active photonic circuit, has so far not been investigated. Here we report on a wavelength splitter based on SP resonance (SPR) by placing a diffractive grating on a thin metal film. The transmitted beam of certain wavelengths can be selected spatially by changing an illumination angle of a white light source. The proposed SPR scheme can be exploited for optical switching or optical communication systems.

The basic configuration of an SPR-based wavelength splitter is shown in Fig. 1. When white light is incident on a metal film with a given angle satisfying the momentum matching condition between SP waves and photons, only the TM-polarization field is completely transferred to the SP waves and is then converted by the dielectric gratings into a radiative light field. This condition is expressed as

$$k_i = k_{\mathrm{SPR}} - iK = k_0\sqrt{\varepsilon_p}\,\sin\theta_{\mathrm{SPR}} - i\frac{2\pi}{\Lambda}, \tag{1}$$

where $k_i$, $k_{\mathrm{SPR}}$, and $k_0$ are the wave vectors of the transmitted light with $i$th diffraction order, the SP waves, and the incident light, respectively. $K$ is the grating vector, and $\varepsilon_p$ and $\theta_{\mathrm{SPR}}$ are the dielectric function of a glass substrate and the incidence angle at resonance, respectively. The angle of the $i$th diffracted beam is given by

$$\theta_i^T = \sin^{-1}(k_i/k_0). \tag{2}$$

For a fixed wavelength, the number of transmitted beams is determined by the diffraction angle that satisfies the above relation [14]. In this study, a limited range of grating period and thickness is considered to suppress the high-order diffraction beams, so that only the low diffraction orders can radiate into the air.

Taking account of the advantages of a large-area grating pattern for efficient light transmission and the potential application to actual photonic devices, we have utilized a nanoimprint lithography (NIL) in fabricating periodic dielectric gratings on a gold film [15]. As a first step, a 45 nm thick gold film is sputtered onto an SF10 glass after an evaporation of a 5 nm thick titanium adhesion layer. Ar gas (40 sccm) is used under a 4 mTorr chamber pressure at 250 W RF power for gold and at

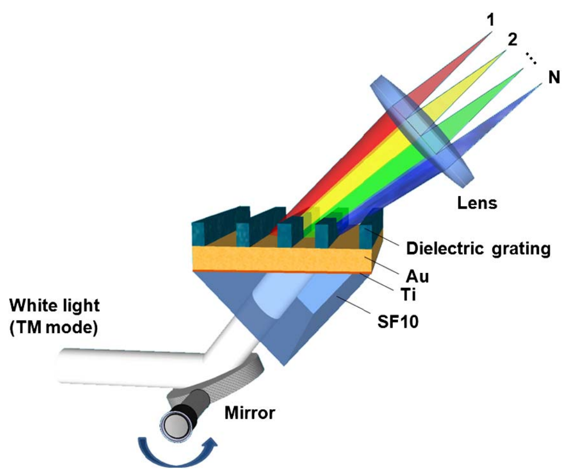


Fig. 1. (Color online) Schematic diagram of the proposed wavelength splitter based on the SPR phenomenon.

 

300 W DC power for titanium. A silicon dioxide ($SiO_2$) layer with a thickness of 100 nm is then deposited on the gold film via electron beam evaporation at room temperature. Before pressing the stamp that contains a designed grating structure into the imprint resist (NIP-SC58LV100, Chem Optics, Korea), an additional film of polymethyl methacrylate (PMMA) is spin-coated, so that this PMMA film acts as a cushioning layer that protects the fragile nanoscale features on the stamp surface. After a 200 nm thick PMMA layer is obtained at a speed of 1000 rpm for 60 s, it is baked at 170 °C for 300 s. During the NIL patterning process, a large-area stamp with high feature density creates a deep thickness contrast of about 150 nm in the imprint resist. After the stamp is peeled off from the substrate, the PMMA and $SiO_2$ layers are etched by $O_2$ plasma ashing for 120 s and by anisotropic dry etching with a 9∶1 $SF_6$-$O_2$ mixture for 60 s, respectively. Finally, the residual polymers are removed by acetic acid and distilled water. As a result, a large-area pattern of dielectric gratings could be achieved successfully using our NIL-based fabrication process.

Scanning electron microscope (SEM) images of the fabricated samples are presented in Fig. 2. The average period, width, and depth of the $SiO_2$ gratings are 400, 200, and 100 nm, respectively. Total effective area of the patterned dielectric gratings is approximately 5 mm × 5 mm. Since the coefficient of size variation is found to be less than 5%, we confirm that the dielectric arrays have been fabricated with good uniformity. Thus, our NIL-based implementation is an effective way to develop a large-area periodic subwavelength pattern.

To analyze theoretically the SPR characteristics of the fabricated sample, we use rigorous coupled-wave analysis (RCWA), which has been frequently applied to explaining optical responses of periodic structures [16]. For simplicity in analysis, the dielectric grating is modeled as a rectangular-shaped array. Wavelength-dependent optical constants of gold, titanium, SF10, and $SiO_2$ are taken from [17]. Figure 3 shows the resonance

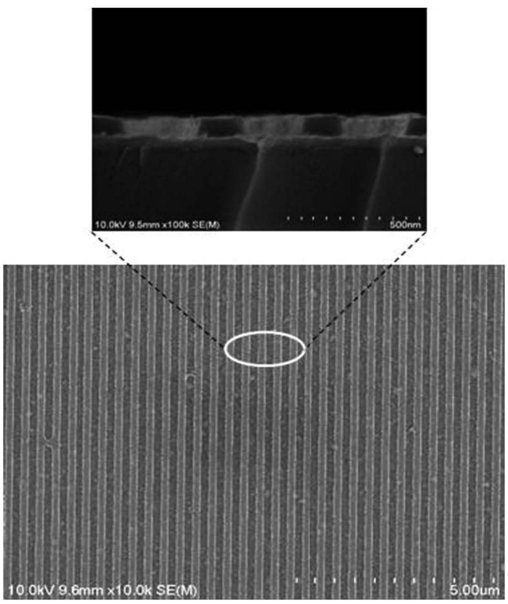


Fig. 2. SEM images of the fabricated array pattern of $SiO_2$ gratings on a gold/SF10 glass substrate.

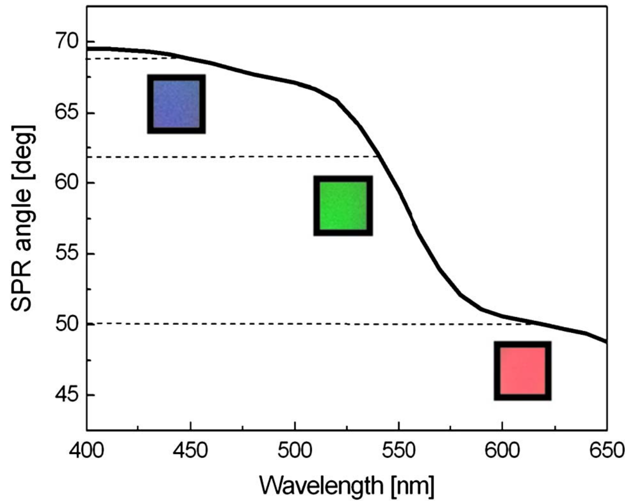


Fig. 3. (Color online) SPR angle curve of the fabricated sample (solid curve). Each color image indicates the experimental results of the diffracted beam obtained by changing the incidence angle of the white light source.

curve of the obtained SPR sample as a function of the wavelength. Since individual wavelengths are completely absorbed at corresponding resonance angles, it is possible to control the color of the diffracted beam by rotating a mirror mechanically. For example, we find that the radiation mode is decomposed into the three colors of red (R), green (G), and blue (B) by choosing the SPR angle in white light illumination (Dolan-Jenner DC-950H, Edmund Optics, USA). In Fig. 3, the incidence angles for the three colors are 68.5° for B, 62.0° for G, and 50.0° for R. Theoretical and experimental results show that the peak wavelength can be continuously tuned from 400 to 650 nm in the visible band by changing the incidence angle.

Subsequently, in order to demonstrate the use of SPR-based light radiation in different directions as a wavelength splitter, we measure the transmission spectra when the fabricated sample is illuminated by a wedge-type white light source. A wedge-shaped beam providing a continuous interval of light wave vectors simultaneously is proper for multiple excitation of SP waves of different wavelengths at one time. While SP waves of different wavelengths can be generated and deflected into different directions by rotating the mirror mechanically, its low switching speed in the millisecond regime inevitably reduces the extent of the application of radiative modes. Thus, in this experiment, a fixed mirror and converging lens are utilized in the frontal end of white light incidence.

When the SPR sample with a dielectric grating is illuminated with a wedge-shaped white light, a variety of colors are generated at corresponding SPR angles determined by the resonance characteristics in Fig. 3. Then, different colors leave the substrate at different transmission angles, creating a colorful band similar to a rainbow. By aligning an iris diaphragm with a radiative mode with a diffraction angle obtained from Eq. (2), we can selectively extract a specific wavelength band from the constituent spectrum of an original white light.

Figure 4 shows the experimental setup based on wedge-type white light and transmission spectra measured at three detection points where the colors of

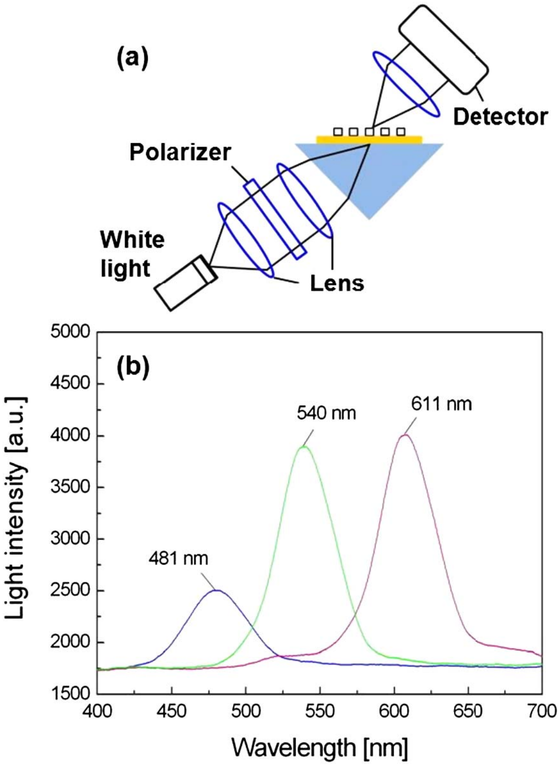


Fig. 4. (Color online) (a) Experimental setup based on wedge-type white light illumination and (b) transmission spectra when the wedge-type white light is incident to the fabricated SPR sample.

R, G, and B are found. As a scanning angle increases, the transmission peak shifts to a shorter wavelength and peak wavelengths are found at 611, 540, and 481 nm, respectively. While the experimental results display a relatively wide bandwidth of about 45 nm, this can be improved by optimizing the thicknesses of gold and $SiO_2$ grating layers. In addition, a smaller transmission peak for blue color appears to be associated with two factors. The first one is a nonuniform intensity distribution of the white light source. While its intensity profile is not shown here, the illumination intensity of the halogen bulbs varies with the wavelength and its intensity is found to be weak at short wavelengths in the visible band. The second reason is attributed to some defects in the optical lens, such as chromatic aberration. As blue light is refracted to the greatest extent, followed by green and red light, this color dispersion may affect a momentum mismatch in the resonant excitation of SP waves. To compensate for this, a converging lens in the frontal part needs to be combined with a weaker diverging lens, so that the chromatic aberrations cancel for certain wavelengths.

In summary, we have described an alternative yet effective approach for wavelength selection and division by using dielectric gratings built on an SPR substrate. A large-area grating pattern has been successfully realized via NIL-based fabrication that can allow high-throughput production of the proposed device. When white light is incident with a fixed angle, we find that the peak wavelength of the diffracted light can be determined by the resonance characteristics of the fabricated samples. In other words, the illumination angle is responsible for the color change of the transmission spectrum. In particular, when a wedge-shaped white light is utilized, we confirm not only multiple excitations of SP waves with different wavelengths but also a spatial split of the transmitted light, which demonstrates the potential use for an optical switching device or optical wireless communication system. As a future direction, optimization of structural parameters of dielectric gratings and metallic film will be necessary to produce a higher peak transmission and a narrower bandwidth in the selected wavelength band.

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