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Outcoupling surface plasmons into propagation modes using a subwavelength dielectric grating for device applications

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ABSTRACT

Coupling of surface plasmon polaritons to radiation modes by use of a one-dimensional subwavelength dielectric grating on a thin metal slab is discussed. The surface plasmon waves obtained in Kretschmann configuration are resonant outcoupled to radiation modes by using a subwavelength dielectric grating. A peak outcoupling efficiency is predicted to be 74.57% with rigorous coupled-wave analysis. In addition, potential applications of these results in the design and improvement of various optoelectronic devices, such as polarizers, wavelength filters and biochemical sensors are discussed.

1. Introduction

Surface plasmon resonance (SPR) is one of the well-known optical phenomena that have been widely applied in many device designs and applications, including electro-optics modulators [1–3], plasmonic filters [4–6], ultrahigh sensitivity chemical and biological sensing [7,8] angular [9] and temperature [10,11] measurements, etc. Most of these devices work as reflection types by use of a standard Kretschmann configuration [12], which connect reflected light to other external optical passive or active devices. Sometimes, the reflection-type configuration might have limitations for implementation of photonic integrated circuits, guiding optical and sensing applications. For example, most SPR-based sensors work as reflection types in the sense that a photodetector measures reflected light from the sensor surface using a configuration of attenuated total reflection (ATR). Such a setup uses a photodetector on the same side of a light source with respect to the metal film, which allows an extremely compact sensing scheme. However, the detectable range of the reflection-type SPR sensors is limited to the penetration depth in the 100–200 nm range because the surface plasmon waves propagate along the metal surface and decay exponentially into both media [13]. Thus, a transmission-type SPR structure might be useful to investigate thick targets such as in cell analysis, in contrast with a traditional reflection-type structure. In a transmission-type SPR sensor, surface plasmons were outcoupled into radiation modes by use of a waveguide layer, in which the permittivity of the waveguide layer is periodically modulated. Coupling of surface plasmons with a diffraction grating has been reported in several other studies [14–16]. Most of these studies consider a corrugated thin-film metal to generate surface plasmons and for outcoupling in radiation modes. However, as mentioned by Park et al. [17], conversing of surface plasmons into only reflection modes that may not have enough to connect the radiation modes from the diffract gratings directly to other external optical devices. To overcome this limitation, they utilized dielectric diffraction gratings for efficient outcoupling of surface plasmons to transmission modes that propagate in free space. An outcoupling efficiency of 50% was presented and proved experimentally by use of a conventional Kretschmann configuration and a dielectric grating on a silver film. From the report of Lenaerts et al. [18], transmittance of 68% was obtained for a modified structure in which a waveguide grating is added between a metal surface and air. Such the gratings are composed of with two king dielectric material, which will intent the complexity of fabrication process. Moreover, enhanced transmittance of up to 72% was predicted numerically by Shen et al. [19] through a thin metal slab with dielectric grating.

In this paper, we investigate resonant coupling of surface plasmon polaritons to radiation modes through a thin metal slab with one-dimensional subwavelength dielectric grating by use of rigorous coupled-wave analysis (RCWA) [20–23]. We describe the method that we have applied to optimize the configuration and how we obtain an outcoupling efficiency of 74.57%. The proposed structure may be used as a polarizer with high polarization beam separation performance. In addition, based on the configuration, a transmission-type surface plasmon resonance biosensor is pre-

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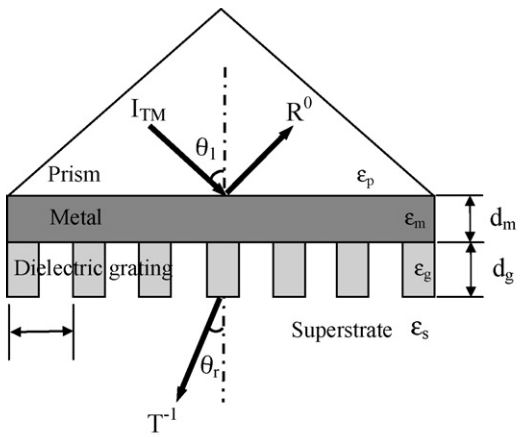

Fig. 1. Schematic of the proposed structure discussed in the paper.

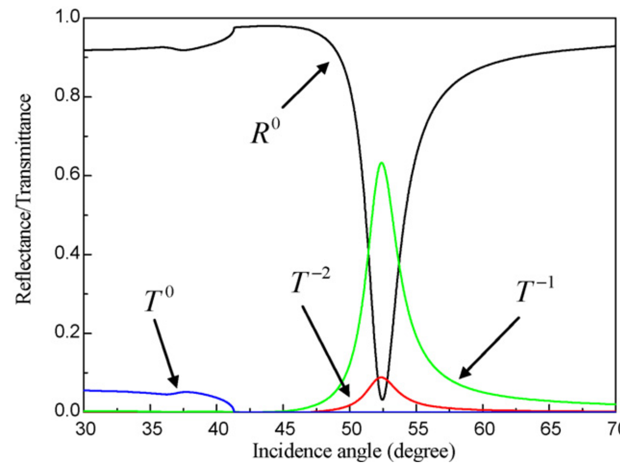

Fig. 2. reflectance (R^0) and transmittance (T^0, $T^{-1}$and T^{-2}) plotted as a function of incidence angle. $\varepsilon_s = 1$ and $d_g = 110$ nm. At $\theta_1 = 54.20^\circ$, $T_{max} = 63.264\%$.

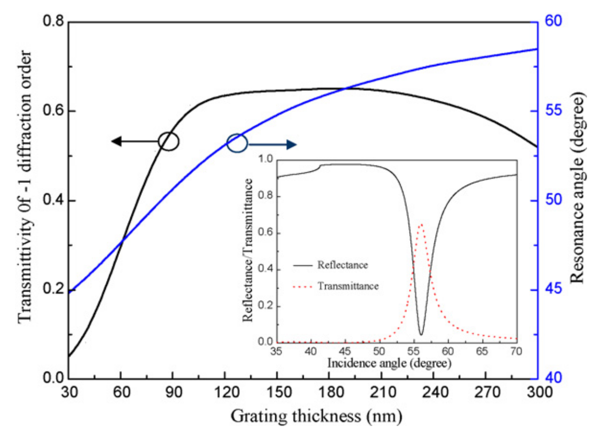

Fig. 3. Influence of the thickness of the dielectric gratings on the transmittance efficiency ($-1T$) and the resonance angle. The inset shows the reflectance (R^0) and transmittance (T^{-1}) plotted as a function of incidence angle for the case of $d_g = 180$ nm. At $\theta_1 = 55.96^\circ$, $T_{max} = 65.263\%$.

sented. Compared with the traditional reflection-type SPR sensor, the new method provides larger detectable range, which might be useful to investigate thick targets such as cell analysis. Numerical simulations show that the biosensor present extremely linear sensing characteristics and its refractive-index (RI) detection sensitivity can be improved by use of a lower refractive-index glass prism.

2. Proposed structure

Fig. 1 shows a schematic diagram of attenuated total reflection (ATR) for generation and outcoupling the surface plasmons with a grating structure, where dielectric grating are represented as a one-dimensional array sit on 40 nm thick silver layer ($d_m = 40$ nm). In the diagram, d_g represents the height of the dielectric grating. Λ is the period of the dielectric gratings. The permittivity of BK7 glass prism, dielectric gratings and metal layer were determined as $\varepsilon_p = 2.2958$, $\varepsilon_g = 2.25$ corresponding to PMMA, and $\varepsilon_m = -18 + 0.5i$ for silver at $\lambda = 633$ nm, respectively.

When TM-polarized light is incident on a prism, the dispersion relation of the excited surface plasmon at resonance conditions is given by

$$k_{SPR} = k_0\sqrt{\varepsilon_p}\sin\theta_{SPR} = Re\left(k_0\sqrt{\frac{\varepsilon_m\varepsilon_d}{\varepsilon_m+\varepsilon_d}}\right) \qquad (1)$$

here, k_{SPR} and k_0 denote the wave vectors of the surface plasmon and the incident light. ε_d is the dielectric constant of the superstrate on top of a metal film. 'Re' denotes the real part of the term in parentheses. This relation indicates that a propagating surface plasmon along the metal surface is converted to a radiation mode by a diffraction grating when the diffracted angle, θ_r, satisfy momentum matching between surface plasmons and photons given by

$$k\sin\theta_r = k_{SPR} + qK, \quad q = 0 \pm 1 \pm 2\ldots \qquad (2)$$

where, k is the magnitude of the wave vector of diffracted light, q is the diffraction order, and $K(=2\pi/\Lambda)$ is the grating vector.

Using rigorous coupled-wave analysis we numerically estimate the diffraction efficiency of the radiation mode in the proposed structure considering an incident TM wave with a wavelength of 633 nm. The grating period, Λ, is defined as 600 nm when the line width is 300 nm (VF = 0.5). This is almost equal to the wavelength of an incidence light, so that only the low diffraction orders can transmit into air. The calculated reflection and transmission curves for the case of $d_g = 110$ nm are shown in Fig. 2. It is obvious that the -1 diffraction order (T^{-1}) is to be selected as the target under interrogation instead of T^0, since T^{-1} is the indicator of a radiation mode.

3. Parameter optimization

The coupling coefficient of the surface plasmon with the diffraction grating depends strongly on the grating parameters of the surface-relief profile, such as period, aspect ratio, and modulation depth [14]. Fig. 3 presents the transmittivity of the -1 diffraction order (T^{-1}) and corresponding resonance angles, as the grating thickness d_g varies from 30 to 300 nm. The transmittivity of -1 diffraction order rapidly increases first to 61.46% until d_g reaches 100 nm, and then it becomes nearly constant. As the thickness exceeds 260 nm, a slight decrease in transmittance appears since other diffraction orders become significant. The peak efficient obtained was $T_{max} = 65.263\%$ at a thickness of $d_g = 180$ nm. The inset shows the resonance characteristics for the case of $d_g = 180$ nm. Also, the resonance angle increase monotonically with grating thickness as the change in d_g causes the local effective index to increase effectively. Results of approximately 68% of transmittance can be found in the literature for similar systems [18].

A new study has been carried out to optimize the device to reach at least the results published in the literature. So the period of the dielectric gratings is still to be determined. Fig. 4 presents the transmittivity of the -1 diffraction order (T^{-1}) and corresponding resonance angles, as the grating period Λ varies from 500 to 800 nm. The outcoupling of the electromagnetic energy toward the air space is maximum if the period of grating is $\Lambda = 560$ nm. With