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Excitation of multi-order guided mode resonance for multiple color fluorescence enhancement

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ABSTRACT

Higher-order Guided Mode Resonance (GMR) in a symmetric two-dimensional embedded grating-waveguide structure is theoretically demonstrated in this paper through a phase matching mechanism of leaky modes along second-order diffraction planes. In addition to the fundamental-order, multiple resonances are introduced at normal incidence and they are polarization independent. A strong localization of the resonance modes exists in both orders. The device is proposed for multiple color surface enhanced fluorescence that is compatible to a conventional fluorescence reader. The enhancement scheme is by increasing light absorption via the excitation of a strong evanescent wave as an extension of a resonance mode. GMR device is designed to have resonances overlapping fluorophores' absorption spectra. The concept is verified using numerical calculations, Rigorous Coupled Wave Analysis and Homogeneous Waveguide Approach. The device is fabricated and experimentally performed for fluorescence enhancement using a microarray of Cyanine 3-labeled goat antibody and Cyanine 5-labeled goat antibody. The fluorescence signal is characterized using a low-cost CMOS array. This implementation can be very useful in a multiplex detection, where the cost of the reader can be minimized.

1. Introduction

Guided Mode Resonance (GMR) in a dielectric grating-waveguide structure [1–4] has been constantly studied and demonstrated in diverse applications. The resonance is due to phase matching of the diffraction waves and the guided modes in the structure. At resonance, light is coupled to a waveguide mode via diffracted waves and it is slowly leaked out with a constructive phase back to the incident side. That introduces total reflection with high spectral and angular selectivity. GMR devices were proposed for narrow band spectral reflection filters [5,6]. They were later applied for other filtering applications such as laser cavity's mirrors [7], polarizers [8], and color filters [9]. Following the resonance's phase matching mechanisms, resonance shifts proportional to an incident angle, as well as the structure's parameters (film's optical properties and dimensions) and surrounding refractive index. GMR based devices have been utilized as a refractive index sensor [10–13]. By integrating a sensing layer on the surface, GMR has been as well demonstrated for several label-free biosensors such as detection of virus [11], bacteria [12], and cellular interaction [13]. Resonance shifts proportionally to a molecular adsorption on the sensing film.

At resonance, field localization occurs in the film layer, which allows GMR to be used as an efficient absorber in thin-film solar cell [14]. The field localization also introduces a strong evanescence wave as an extension of the resonance mode. Hence, GMR has been reported for surface enhanced emission in fluorescence –based biosensor [15] as well as in light emitting device [16,17] and for enhancing nonlinear harmonic generation in azo-polymer [18]. The enhancement approach is by increasing light excitation to fluorophores via a strong evanescent wave. This is the case when resonance matches the absorption peak of the fluorophores. More photon extraction is obtained when matching another resonance at the emission spectrum. Hence, multiple resonances are necessary specially to enhance multiple spectral emission.

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Multiple resonances occur in a multimode waveguide configuration [19–21] where thicker film structure is necessary. Resonance separation relies on modal characteristics in the structure. More resonances are presented at oblique incidence due to breaking the symmetry of the diffraction. Recently, GMR with one-dimensional (1-D) grating was reported for multiple color-surface enhanced fluorescence [22] and for enhancing both excitation and extraction of two-photon photoluminescence [23] when operating at oblique incidence. Customized fluorescence detection system is however required. Another approach is to allow multiple planes of diffraction using two-dimensional (2-D) grating [24]. The resonance modes can be performed individually along each fundamental diffraction plane. Resonances are better controlled through the grating's periodicities. 2-D structures with a rectangular periodicity have been demonstrated for surface enhanced fluorescence to improve both excitation and extraction corresponding to resonances along each periodicity [25–27]. Resonances are polarization sensitive.

While most of the researches on GMR focus on the resonances from the first-order diffraction, the ones from higher orders have not received similar attention. Higher order excitation causes some energy loss to the substrate especially in structures with low refractive index contrast. Although, light is partially reflected and transmitted, field localization with a strong evanescent wave on the surface still exists at resonance. Having higher-order diffraction planes in 2-D structure, higher-order resonances can be excited through the second-order planes of diffraction. This results in higher-order resonances with less energy loss. Resonances can be as well polarization independent when utilizing symmetric diffractions. GMR having a symmetric 2-D grating is proposed in this study for enhancing the fluorescence signal of multiple color fluorescent dyes. The device can be operated at normal incidence and it is compatible to most of conventional fluorescence readers such as fluorescence optical microscope or microarray laser scanner. This can be useful for complex analyzed sensors such as application in Gene expression [28] or cell analysis [29]. The implementation can be extended towards a low-cost fluorescence reader using a CMOS camera.

In this paper, resonances in a symmetric 2-D GMR are theoretically demonstrated for two-color surface enhanced fluorescence, where the first-order and the second-order resonances overlap the absorption spectra of two fluorescent dyes (excitation/emission in green and red spectrum). The resonance concept is verified using numerical calculations, Rigorous Coupled Wave Analysis (RCWA) [30,31] and Homogeneous Waveguide Approach (HWA) [6]. The GMR devices are realized through coating a high refractive index film on a lower refractive index grating. This allows for the production of multiple devices with comparable optical response. The grating pattern is first fabricated using laser interference lithography approach, then it is duplicated using nanoimprint technique. The duplicated grating is finally coated with high refractive index film by sputtering technique. The fabricated GMR is optically characterized and compared to the calculations. The fluorescence enhancement is experimentally demonstrated by printing a microarray of Cyanine 3-labeled goat antibody and Cyanine 5-labeled goat antibody with varying concentrations on the device. The fluorescence signal is determined using a low-cost fluorescence imaging. The signal enhancement in both fluorescent dyes was shown especially in Cyanine 5 (up to 43 times). Low enhancement in Cyanine 3 (factor of 2) is due to the excitation of the cladding mode first-order resonance (field localized in the lower index film under the grating). Further enhancement is feasible via optimization of GMR structure to excite the core mode second-order resonance (field localized in the high index film nearby the device's surface) as will be demonstrated in the calculations.

2. Resonance in a symmetric 2-D GMR

Here, a 2-D GMR having an embedded grating-waveguide structure is demonstrated in Fig. 1a. The grating has a periodicity along two directions with skew angle of ζ and periods of Λ_a and Λ_b. In a symmetric pattern, the periods are equal ($\Lambda_a = \Lambda_b = \Lambda$). The skew angle is $\zeta = 0°$ for square-grid pattern and $\zeta = 30°$ for hexagonal-grid pattern. To simplify the calculations, a cylindrical air-hole profile grating with medium refractive index of n_g, radius of r_g, and depth of t_g is assumed. The structure also includes a film under the grating (with the same medium refractive index of n_g and thickness of t_{gf}) as a result of nano-imprint fabrication method used in this paper. The high refractive index film having refractive index of n_f and thickness of t_f is deposited on the grating introducing an optical waveguide.

In 2-D GMR, the phase matching condition between the diffraction waves and the waveguide modes can be introduced in separate planes. The incident light is diffracted along the reciprocal planes (k_x, k_y) following the grating equations.

$$k_{x,pq} = k_{x,inc} - \left(p\frac{2\pi}{\Lambda_b}sec(\zeta) + q\frac{2\pi}{\Lambda_a}tan(\zeta)\right),\quad k_{y,pq} = k_{y,inc} - \left(q\frac{2\pi}{\Lambda_a}\right). \tag{1}$$

where $k_{x,inc}$ and $k_{y,inc}$ are the propagation constants of the incidence wave in x- and y-directions respectively. $k_{x,pq}$ and $k_{y,pq}$ are the propagation constant of (pth, qth)-order diffracted waves. The order is defined along x- and y-axis, respectively.

Due to the presence of higher-order diffraction planes in the 2-D grating, the (ith) diffraction order is represented here using the value of the propagation constant (k_i).

$$k_i = \sqrt{{k_{x,pq}}^2 + {k_{y,pq}}^2}. \tag{2}$$

Thus, resonance is obtained when the propagation constant of the waveguide mode (β_m, -mth is the mode order) satisfies the phase matching condition$k_i \approx \beta_m$. For a 2-D GMR having a square-grid grating, the symmetric diffraction pattern is shown in Fig. 1b when operating at normal incidence. The second-order resonance can be excited via the second-order diffraction (i = 2 or (p, q) = (±1, ±1)), where the resonance mode propagates along the second-order diffraction plane (2nd plane). Likewise, the first-order resonances are excited along the first-order diffraction plane (1st plane: i = 1 or (p, q) = (±1, 0) and (0, ±1)). At normal incidence, resonance for each order occurs at two wavelengths correlating to TE and TM resonance mode. Due to the symmetry of the diffraction pattern, resonances are not sensitive to the polarization of the incident light. The separation of resonances can be optimized via the grating periodicity and the waveguide's parameters.

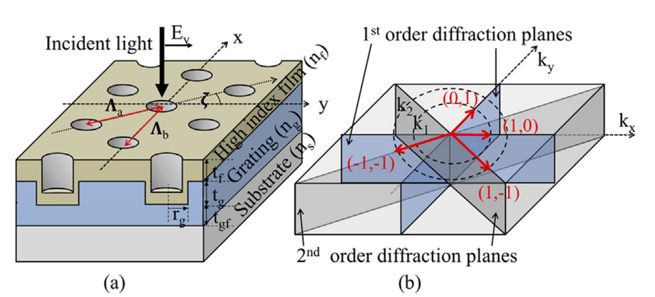

Fig. 1. Schematic of a 2-D GMR (a) and symmetric diffraction planes in a square-grid grating when incident light at normal incidence (b).