

Sensitive metal layer assisted guided mode resonance biosensor with a spectrum inversed response and strong asymmetric resonance field distribution

Sheng-Fu Lin,¹ Chih-Ming Wang,² Ting-Jou Ding,¹ Ya-Lun Tsai,¹ Tsung-Hsun Yang,¹
Wen-Yih Chen,³ and Jenq-Yang Chang^{1,4,*}

¹Department of Optics and Photonics, National Central University, Zhongli 32001, Taiwan

²Institute of Opto-Electronic Engineering, National Dong Hwa University, Hualien 97401, Taiwan

³Department of Chemical and Materials Engineering, National Central University, Zhongli 32001, Taiwan

⁴Optical Science Center, National Central University, Zhongli 32001, Taiwan

*jychang@dop.ncu.edu.tw

Abstract: In this paper, a metal layer assisted guide mode resonance (MaGMR) device with high sensitivity is proposed for bioanalytical applications and its functioning is experimentally proved. We find that the reflection spectra present a unique inversed response. The resonance mechanism is also discussed. Numerical calculation results indicate that the high sensitivity performance of MaGMR comes from the strongly asymmetric resonance modal profile and low propagation angle inside the waveguide. There is a one-fold enhancement of the evanescent wave in the analytes region compared to typical GMR. According to the experimental results, the proposed MaGMR achieved a bulk sensitivity of 376.78nm/RIU in fundamental TM mode resonating at 0.809 μ m with the first diffraction angle. Experiment results show a 264.78% enhancement in the sensitivity compared to that of the typical GMR sensor in the same resonance conditions of TM mode.

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OCIS codes: (050.6624) Subwavelength structures; (130.2790) Guided waves; (230.1950) Diffraction gratings; (260.3910) Metal optics; (280.4788) Optical sensing and sensors.

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1. Introduction

Biosensing has become more crucial because a number of specific molecules are proven biomarkers for certain diseases [1–3]. The interaction between the biomarkers and their ligands is an important and fundamental aspect of the study of bioanalytical applications, in areas such as drug development, and point of care diagnosis. Various label-free transducer technologies have been developed for biosensing, including piezoelectrical [4,5], electrical [6–8] and optical transducers. Optical transducers, such as surface plasmon resonance (SPR) [4,9,10], whispering gallery mode [11,12], and guided mode resonance (GMR) [13–16] sensors are extensively applied in bioanalytical applications because of their high sensitivity, high stability, and simple measurement setup.

The GMR filter had been already been utilized for biosensing. In early 2000, wavelength and angular resolved GMR sensors were first realized by Wawro et al. [17] and Kikuta et al. [18]. However, the sensitivity of these GMR sensors was still inferior to that of the SPR sensors. As a consequence, over the past decade, several groups have focused on enhancing the sensitivity of GMR sensors [14,16,19–21]. In optical transducers (i.e., GMR sensors), the sensing ability is proportional to the overlap intensity of the analytes and evanescent waves

outside the structure [14]. Furthermore, a general binding reaction usually occurs within few tens to hundreds of nanometers from the sensor surface, depending on the size of the biomolecules or analytes. Therefore, the design of evanescent wave with a high intensity and long extending length at the sensor surface is crucial for high sensitivity optical sensors. The structure of GMR sensors is a combination of waveguides and diffraction gratings. Consequently, manipulating the geometric structure of the GMR sensor opens a way to modulate the strength and distribution of the evanescent wave [22].

In this study, we propose a highly sensitive metal layer assisted guided mode resonance (MaGMR) device for bioanalytical applications. To enhance device performance, a metal buffer layer is used to modulate the evanescent wave so that there is a strong asymmetric resonance profile in the sensing region. There are several methods that can be also used to enhance the sensitivity of GMR sensors. The MaGMR method proposed in this study is based on the following considerations:

- (1) Studies indicate that it is the higher critical angle from the waveguide bottom interfaces (i.e. the opposite to the sensing layer) that reduces the sensitivity of GMR sensors. The sensitivity can be enhanced if the higher critical angle is avoided [23]. The use of a porous low refractive index substrate [16] or a symmetric free-standing GMR structure [14,23] to enhance the sensitivity has been examined in some studies. However, the higher critical angle problem still exists in low index substrate cases. In the symmetric GMR case, the higher critical angle is avoided by overlapping the top and bottom critical angles; however, the ultra-thin waveguide structure makes fabrication and measurement difficult and the device fragile. The use of MaGMR totally solves the second higher critical angle issue and the fragility problem.
- (2) A GMR sensor is a high resonance device, thus, the high confinement of the waveguide must be well satisfied. Metals reflect light waves in any direction due to their high reflectivity, thus, high confinement for high quality factor resonance can be easily reached at any propagation angle.
- (3) Given the boundary conditions, the electrical field cannot extend into a perfect conductor. Therefore, MaGMR supports an asymmetric resonance field, which only extends into the top side. In contrast, the evanescent wave of typical GMR sensors extends out of both sides while the MaGMR provides stronger evanescent waves on the sensing side.

Based on the above considerations, MaGMR provides a solution for use in high sensitivity biosensor. The low sensitivity second critical angle issue is avoided. MaGMR offers an asymmetric modal profile and a robust structure which makes it suitable for bioanalytical applications.

2. Concepts and model

A sketch of a high refractive index planar waveguide and subwavelength grating on a substrate composed of a typical GMR device is shown in Fig. 1(a). The GMR structure offers a narrow band peak in the reflection spectrum [13,15,24]. In the MaGMR cases, a high reflectivity metal layer is simply added between the substrate and the waveguide, as shown in Fig. 1(b). The design of the MaGMR allows energy transformation from the diffraction gratings to the guiding layer. Thus, a subwavelength grating is used to provide the incident light an additional lateral momentum so that resonance occurs when the diffracted light matches the guided wave condition of the planar waveguide. In this configuration, the total phase shifts from the top, rear interfaces and transverse phase must be a positive multiple of 2π ; so, the guide wave condition in MaGMR can be expressed as

$$k_0 n_{wg} h \cos(\theta) - m\pi = \phi_{top} + \phi_{bottom}, m = 0, 1, 2, \dots, \quad (1)$$

where k_0 is the wave-number in a vacuum, that is, $(2\pi/\lambda)$; λ is the wavelength; n_{wg} stands for the refractive index of the waveguide; h is the waveguide thickness; m is a positive integer that stands for the mode number of a waveguide (i.e., fundamental mode: 0); and θ denotes the angle of propagation inside the waveguide, as shown in Fig. 1(a). The $\phi_{top/bottom}$ represents half of the phase shift from the top and bottom interface. The terms $(k_0 n_{wg} h \cos(\theta))$ and $(\phi_{top} + \phi_{total})$ are also called the propagation phase relation (structure relation) and phase shift relation (interface relation), respectively. When the waveguide structure is determined, the grating period which diffracts the specific wavelength into the waveguide can be calculated with the following diffraction equation:

$$\Lambda(n_{wg} \sin(\theta_d) - n_c \sin(\theta_i)) = m_g \lambda, m_g = 0, 1, 2, \dots, \quad (2)$$

where Λ is the grating period; n_c is the effective cover index above the MaGMR device; θ_{id} stands for the incident/diffraction angle of the light; and m_g denotes the diffraction order of the grating. In resonance conditions, the angle of diffracted light (θ_d) must equal the angle of propagation inside the waveguide (θ). Furthermore, Eq. (1) only presents a single wavelength behavior. The MaGMR is a spectrum resolved device; Eq. (1) must be modified to solve multi-wavelength problems. According to our previous study [23], Eq. (1) can be transformed into a multi-wavelength behavior equation by a few steps in a mathematical process. The modified Eq. (1) for multi-wavelength behavior can be expressed as

$$k_g m_g h \cot(\theta) - m\pi = \phi_{top} + \phi_{bottom}, m = 0, 1, 2, \dots, \quad (3)$$

where $k_g = (2\pi/\Lambda)$. The variables in Eq. (3) only depend on the geometric parameters of MaGMR, such as the grating period, waveguide thickness and materials. Through Eq. (3) and (2), the resonance wavelengths for any MaGMR structure can be solved and vice versa.

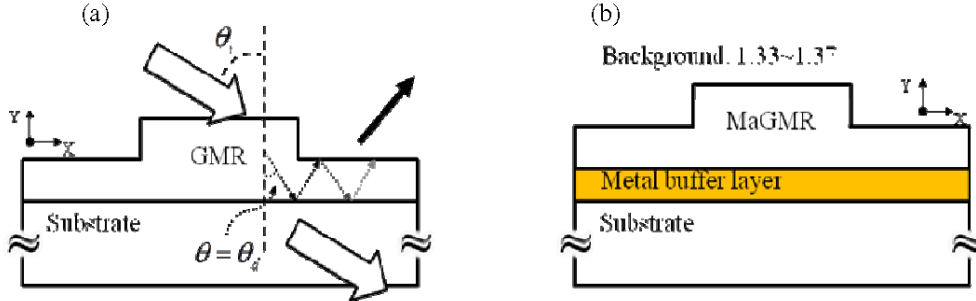


Fig. 1. (a) Typical GMR structure supported by a substrate. (b) Proposed MaGMR structure with the addition of a metal buffer layer between the substrate and the GMR structure. One unit cell is sketched.

The finite-difference time-domain (FDTD) method was used to carry out the simulation in this study. The refractive index of the substrate was set to 1.45 (SiO_2), a metal buffer layer (gold was used in this study) was selected as the dispersive medium according to the Palik material database [25], the high index waveguide was set to 2.05 (Si_3N_4), and the background (top region) indices varied from 1.33 to 1.37, as shown in Fig. 1. The boundaries were set to be periodic in the X direction to emulate the infinite planar wave and structural periodicity, and perfect match layers (PMLs) were assumed at the Y boundaries to absorb the outgoing electromagnetic fields. The planar wave light source was linearly polarized in the Z direction defined as transverse electric (TE) polarization. The source propagated in the Y direction and normally impinged on the structures from the top to the substrate. The FDTD method was used to calculate both the reflections and the field distributions. The grid sizes were set as one order smaller than the shortest length in the model structures.

3. Simulation results

3.1 Spectrum inversion and resonance mechanism

In order to highlight the performance and features of the MaGMR device, all the simulation results here were compared with the GMR results. The MaGMR and GMR exhibit totally different reflection spectra, as shown in Fig. 2(a). Figure 2(a) shows the reflection spectra of the MaGMR and GMR, in which the horizontal axis is the wavelength and the vertical axis is the reflectance. The calculated structural parameters for the MaGMR and GMR devices are shown in Table 1. Both resonance wavelengths were designed at approximately $0.804\ \mu\text{m}$, and resonated at the first diffraction order of the grating, limited to the lowest accepted propagation angle. The waveguide mode was also limited to a fundamental TE mode.

Table 1. Simulation parameters

	GMR	MaGMR
Period (μm)	0.515	0.575
Gold buffer layer (μm)	0	0.1
Waveguide thickness (μm)	0.07	0.11
Grating depth (μm)		0.05
Filling factor		0.5
Superstrate R.I.		1.33
Grating and waveguide R.I.		2.05
Substrate R.I.		1.45

The spectrum of the MaGMR exhibits high reflectivity side bands and a low reflection resonance wavelength while the GMR shows a total reflection resonance peak and low reflectivity side bands. The contrast ratios calculated from the spectra are 23.5 and 10 for MaGMR and GMR, respectively. Physically, the resonance waves of the GMR and MaGMR both stay in waveguide for a long duration. This can be seen from the calculation results as shown in Fig. 2(b). Figure 2(b) shows the intensity of the electric field of both MaGMR and GMR inside the waveguide against time. The red lines in Fig. 2(b) show the fitted decay envelopes. The E field intensity before 40fs is a mixture of input source and non-resonance reflections which are not used to calculate the decay rate. The decay constants of the guiding waves in GMR and MaGMR are -0.01375 and -0.01533 , respectively, which indicates that the guiding wave in the MaGMR decays faster than the GMR. In the GMR case, the guiding wave propagates in the waveguide by means of total internal reflection (TIR) except for the grating region. Because of structural perturbation from the gratings, the resonance energy is subsequently gradually re-emitted back to the top region as the guiding waves touch the gratings. With the continuous source energy input, the resonance energy starts to accumulate until the instantaneous input energy equals the instantaneous leaking energy. However, at the side bands, the energy just goes through the GMR structure, leading to the low reflection shown on the two sides of the spectrum. This is why the resonance peak in GMR is totally reflected and the side bands are always characterized by low reflectivity. On the other hand, in the MaGMR case, although the resonance energy also accumulates in the waveguide, the resonance wavelength never reaches total reflection. The guiding wave in MaGMR has a faster decay rate which is caused by the one leaky and one lossy interface, the grating and metal interface. The energy stored in waveguide not only leaks from the grating but also dissipates from the metal-dielectric interface. Furthermore, the side bands are always reflected by the high reflectivity metal, thus, the spectrum of the MaGMR is inverse to the GMR spectrum and the resonance wavelength exhibits neither total nor zero reflection spectra, as shown in Fig. 2(a).

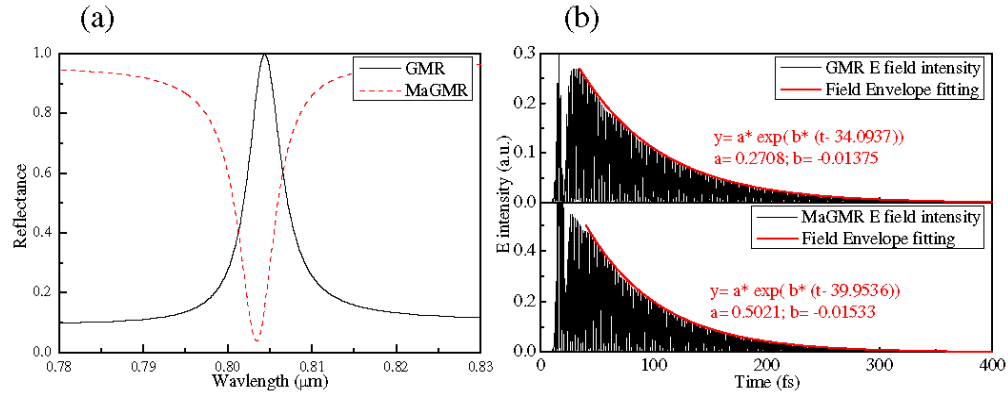


Fig. 2. (a) Simulated reflection spectra of GMR and MaGMR. The GMR spectrum shows a reflection peak at 0.804 μm and the MaGMR spectrum shows a dip at 0.803 μm ; (b) E field intensity inside waveguides. The decay constants for GMR and MaGMR are -0.01375 and -0.01533 , respectively.

3.2 Grating effects

GMR devices are sensitive to changes in the refractive index around its structure. MaGMR devices also respond to changes in the environmental refractive index. Figure 3 shows the relations among the normalized grating depth, resonance wavelength (R. W.), and quality value (Q). The horizontal axis shows the normalized grating depths, which are normalized to the waveguide thickness. As the grating depth increases, both the resonance wavelength of GMR and MaGMR shift to a longer wavelength. According to Fig. 3, the slopes of each of the normalized depth steps for MaGMR are consistently 2 times greater than the GMR slopes (the maximal slopes of GMR and MaGMR in Fig. 3 are 53.125 and 130.75, respectively). This indicates that gratings play a more crucial role in the MaGMR resonance mechanism, which can substantially affect the resonance wavelength. The increase of grating depth can also be considered an increase of the effective refractive index on top of the waveguide surface. Thus, the relative phase shifts on the top surface increase in conjunction with the grating depth. In contrast, Fig. 3 also shows the Q value. The Q value represents the energy stored over the energy dissipated per oscillation cycle or power loss in the resonators. In the case of GMR, the Q value decays as the grating depth increases; however, in the case of MaGMR the Q value is independent of the grating depth. The resonance wave in typical GMR propagates by TIR at the bottom interface of the waveguide. The only leak in the GMR cavity is the grating, thus, the resonance wave is also called the “resonant leaky mode” [26]. In thin grating depth conditions, the diffraction efficiency is proportioned to the grating depth [27]. In other words, the thin grating profile is similar to a plane and has a small diffraction efficiency which is called the weak modulation condition. The diffraction efficiency increases in conjunction with the grating depth. Thus, it is difficult to store high energy in the waveguide as the grating depth increases, which is the strong modulation condition. In MaGMR structures, although the gold buffer layer exhibits high reflectivity, total reflection is never reached; thus, one leaky grating and one lossy metal-insulator interface dissipate the energy inside the waveguide. Therefore, MaGMR exhibits a relatively low Q value compared with the GMR case with small normalized grating depths. A lower Q value stands for a rapid decay in the waveguide. The results of Q factor also agree with the results of the guiding wave decay rate in the waveguide shown in Fig. 2(b).

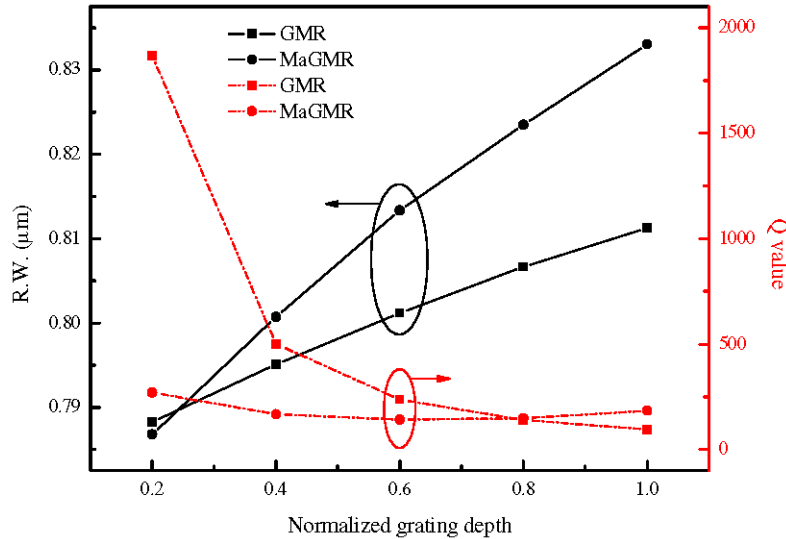


Fig. 3. As the normalized grating depth increases, the resonance wavelengths of both GMR and MaGMR also increase. Given the same normalized depth increase, the increase in resonance wavelength is always greater with MaGMR than GMR. The Q value of GMR decreases as the normalized grating depth increases, but there is no obvious variation in the case of MaGMR.

3.3 Metal removes the second critical angle from the bottom interface

According to our previous study, in GMR biosensors, a higher propagation angle of the resonance wave causes superior confinement of the waveguide but inferior sensitivity to environmental changes (refractive index) [23]. The critical angle at the interface between the substrate and waveguide is usually larger than on the other side (the detection side). Therefore, the propagation angle of the resonance wavelength must be greater than the critical angle of the rear interface of the waveguide. Thus, prior studies show that the refractive index of the substrate could be decreased by using low index glass or a suspended configuration. This would decrease the higher second critical angle and achieve higher sensitivity [16]. Figure 4(a) shows a typical GMR structure (TE mode) derived from Eq. (3), which presents a multi-wavelength solution for a GMR sensor. The X-axis indicates the propagation angle (degrees) inside the waveguide, and the Y-axis is the phase shift (radian) from the interfaces. The phase shift curve shows two turning points that represent the two critical angles from the top and rear interfaces. The cross point of the phase shift curve and structure relation curve is where the resonance occurs. The cross point must be greater than the second critical angle; otherwise, the waveguide will be out of confinement. As the reflective index of the top medium is increased (from 1.33 to 1.34), the phase shift curve shifts to the right (see the green lines in Fig. 4); the cross point and resonance wavelength also shift. The shift of resonance wavelength is proportional to the length of the structure relation curve cut by the two cross points. The maximal phase shift occurs at the first critical angle and decreases with an increasing propagation angle, as shown in Fig. 4. Thus, a resonance wavelength with a low propagation angle is a critical issue to the design of a high sensitivity GMR sensor [23]. In this work, a metal buffer layer (gold) was added between the substrate and the waveguide to remove the low sensitivity second critical angle region while still maintaining high confinement of the waveguide. Figure 4(b) shows the solution of the MaGMR structure (TE mode). The dispersion of the gold is ignored here. The complex refractive index of gold is assumed to be $n = 0.1808 + 5.1173i$ at $\lambda = 0.8\mu\text{m}$ [25]. According to Fig. 4(b), only one turning point for the critical angle is observed, which is caused by the top interface. Thus, the cross point can be designed to be as close as possible to the most sensitive region. In Fig. 4(b),

the phase shift curve is shifted upward because of the additional phase caused from the reflection of dielectric-metal interface. In this case, the phase shifted by 1.28 radian which can be also validated by the Fresnel's reflection coefficient. The thickness of the waveguide must be increased to obtain a solution from an upward shifted phase shift curve.

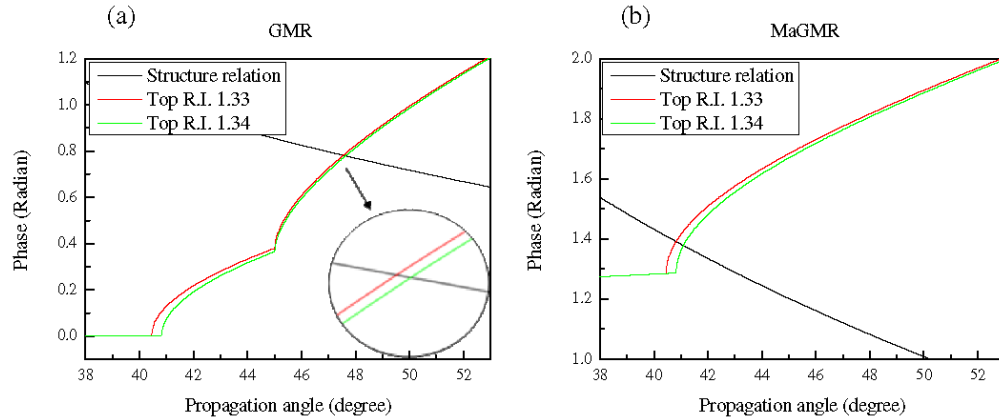


Fig. 4. (a) Solution for a typical GMR. Two critical angles from the top and bottom interfaces are shown at 40.4° and 45° . As the top R.I. increases, the first critical angle shift is to the right (40.8°), and the phase curve shifts as well; (b) for the solution for the MaGMR only one critical angle from the top interface is observed.

3.4 Strong asymmetric field distributions

Figure 5 shows the E field intensity at the resonance wavelength. The white lines are structural outlines, and only one unit cell is illustrated. As shown in Fig. 5(a), the resonance wave is a fundamental mode in the GMR structure, and the evanescent tail penetrates into both the superstrate and substrate. Conversely, as shown in Fig. 5(b), in MaGMR, the field distribution also exhibits a fundamental mode in the structure; however, no energy penetrates to the substrate because of the gold buffer layer. Figure 5(c) shows the total normalized field intensity across the Y direction in one period. The dashed line represents the bottom interface of the waveguide. The ripple shown in the intensity cross section of GMR indicates the interference between the incident and reflected light. In the GMR case, the evanescent field exhibits a larger distribution in the substrate, because the refractive index of the substrate (1.45) is higher than that of the superstrate (1.33). Up to 37.8% of the total resonance energy is distributed in the substrate, which is 51.2% of the total evanescent energy. In other words, more than half of the energy that could be used for biosensing applications is wasted in the substrate. Although the substrate can be replaced with a low index material, the total evanescent field still spends a portion of its energy in the substrate. In other words, the sensing ability of the GMR sensor is limited by the GMR structures. In contrast, in the MaGMR structure, which has a metal layer at the bottom of waveguide, the resonance field shows a strongly asymmetric distribution which extends to the top region. With such a MaGMR structure, the entire evanescent field can contribute to sensing in the top medium. The evanescent energy is 70.8% of the total energy of the enhanced resonance localized field, because of the metal buffer layer. On the other hand, the length of evanescent wave is $0.09\mu\text{m}$ and $0.175\mu\text{m}$ for GMR and MaGMR, respectively. In this case, the evanescent wave gets 94.4% enhancement in length by MaGMR structure. Here the length is defined from waveguide surface to where the intensity drops to a value of $1/e$. Through this configuration, the intensity of the evanescent wave in the top medium is one-fold higher than in a typical GMR device. Thus, a higher response to any perturbation in the top medium is possible in MaGMR structures. These results exactly explain the results in Fig. 0.3. Since the evanescent wave of MaGMR in top region is one-fold higher than that of GMR structure, with the same

incensement of normalized grating depth, the resonance wavelength shifts of MaGMR are two times higher than GMR configurations shown in Fig. 3.

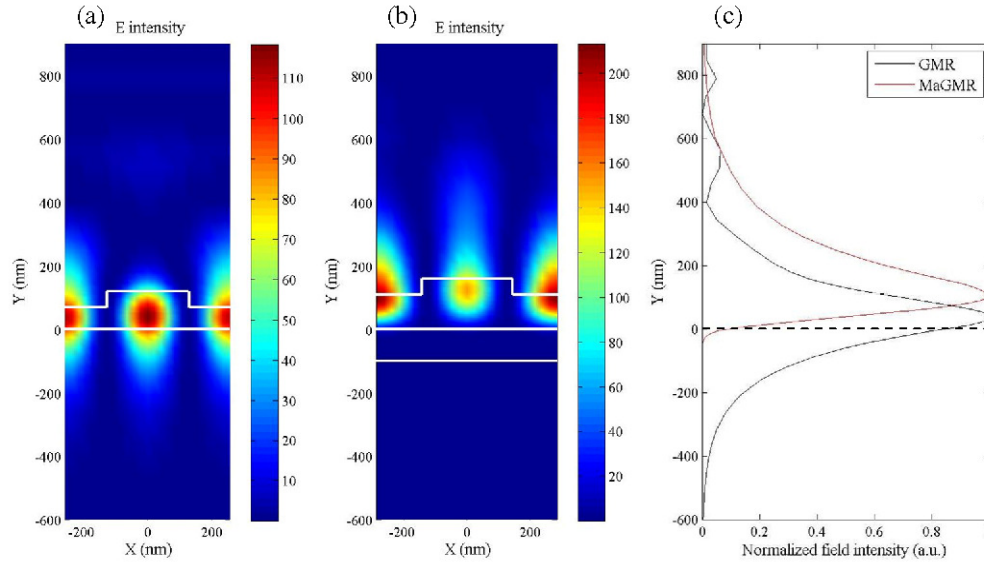


Fig. 5. Resonance field distribution of (a) GMR and (b) MaGMR; (c) normalized field intensity across the Y axis. The dashed line indicates the bottom interface of the waveguide.

In waveguide types of biosensors, the greater the penetration of the evanescent wave into the analyte region the greater will be the response to changes in the analytes [14,22]. A waveguide with optimal confinement usually exhibits a low evanescent wave outside. According to the discussion in Sections 3.3 and 3.4, there are two main mechanisms that contribute to enhancing the sensitivity of the MaGMR structure. One is to reduce the propagation angle inside the waveguide, and the other is to provide a highly asymmetric field distribution. A higher propagation angle inside the waveguide shows that the resonance wave “seems” to propagate along the waveguide direction (in this study, the X direction), exhibiting superior confinement. Decreasing the propagation angle makes the resonance wave “seem” to strike the vertical direction of the waveguide (the Y direction), exhibiting inferior confinement. This “striking” behavior results in a greater difference in the total phase shift curve as shown in Fig. 4. The greatest phase shift is near the first critical angle. Therefore, a metal buffer layer can be added to prevent leakage of the wave at the bottom interface when the propagation angle of the resonance wave is reduced. Furthermore, the electromagnetic field cannot penetrate through the optically thick metal. Consequently, the metal between the substrate and the waveguide forces the waveguide mode to shift upward, which also increases the weight of the evanescent wave in the top region (the analyte region). Both of these mechanisms contribute to enhancing the weight of the evanescent wave in top medium, but with different methods.

3.5 Bulk sensitivity

Spectrum resolved biosensors usually measure the concentrations of analytes by tracking the specific wavelength, such as the resonance wavelength or emission spectrum [10,11,13–15]. A rough indication of the sensitivity of resonance tracking sensors is the bulk sensitivity, usually expressed in units of nm/RIU (RIU: refractive index unit) [14,22]. To evaluate the performance of the structures, the refractive index of the top medium was varied from 1.33 to 1.37. The resonance wavelength increased in conjunction with the top index. The bulk sensitivity can be presented by

$$S = \Delta\lambda / \Delta n_c \text{ [nm / RIU]}, \quad (4)$$

where $\Delta\lambda$ is the shift in value of the resonance wavelength and Δn_c is the change in refractive index of the top medium. An examination of Fig. 6 shows that the resonance wavelength shifts in relation to the top indices. All resonance conditions with a 1.33 top medium index are designed to resonate at 0.8 μ m with the fundamental resonance mode and first grating diffraction order. The data are fitted into a linear function. The slope indicates the bulk sensitivity. As shown in Fig. 6(a), the TE mode sensitivity of the GMR and MaGMR devices is 108.5 and 276.5, respectively. The sensitivity of the TM mode is 136 and 338.5 for GMR and MaGMR, as shown in Fig. 6(b). The MaGMR structure provides an asymmetric modal profile and lower propagation angle inside waveguide; therefore the shifts in the resonance wavelength are always greater than for the GMR structure under the same refractive index perturbations. In this case, the bulk sensitivity was enhanced by 154.8% and 148.9% for the TE and TM mode, respectively. Furthermore, this MaGMR structure can be also applied simultaneously with other sensitivity enhancing methods, such as nano-rod surfaces [19], interrupted waveguides [15], or 2D periodic structure waveguides [14].

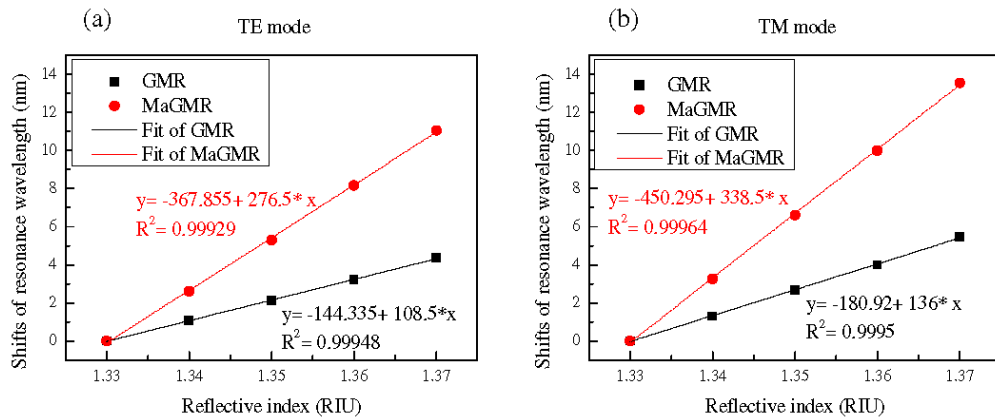


Fig. 6. Sensitivity of the resonant wavelength for GMR and MaGMR in the (a) TE mode and (b) TM mode, in response to changes of the top medium refractive index.

4. Experimental results

In order to validate the high sensitivity performance of the proposed MaGMR structure, a chip was fabricated utilizing the parameters giving the highest sensitivity as mentioned in the previous paragraph for MaGMR in the TM mode. The fabrication of the MaGMR chip began by E-gun deposition of a 100nm Au film on a fused silica substrate. After that, we deposited a Si_3N_4 layer for the high refractive index waveguide and grating layer by plasma enhanced chemical vapor deposition (PECVD). Following this, a grating pattern was recorded in photoresist by laser interference lithography (LIL). Finally, the one dimensional grating was transferred to the surface of the Si_3N_4 through a dry etching method. Figure 7(a) shows a photograph of the MaGMR chip with an effective area of $\sim 1.5 \times 1.5 \text{ cm}^2$ fabricated with the rapid and uniform LIL technique. The thickness of each layer was inspected by scanning electron microscopy (SEM). Figure 7(b) shows the SEM results for a cross-section of the chip which indicates that the thickness of the Au, waveguide and grating are 0.09, 0.24 and 0.04 μ m, respectively. As can be seen in Fig. 7(b) the side wall of the grating is not fully vertical, thus, the weighted average of the top and bottom width is utilized to calculate the grating period and filling factor, which are 0.603 μ m and 0.49, respectively. The properties of the resonance of the TM mode MaGMR in air are explored by reflectance spectroscopy. A tungsten lamp is used as the light source. The reflectance results for the zero-order reflectance

measurement under normal incidence and a numerical calculation are shown in Fig. 7(c). Both results in Fig. 7(c) show an apparent drop at the resonance wavelength and non-resonance side bands are in high reflectivity. A good match between the computed and the experimental results is observed. The resonance wavelength is around $0.742\mu\text{m}$.

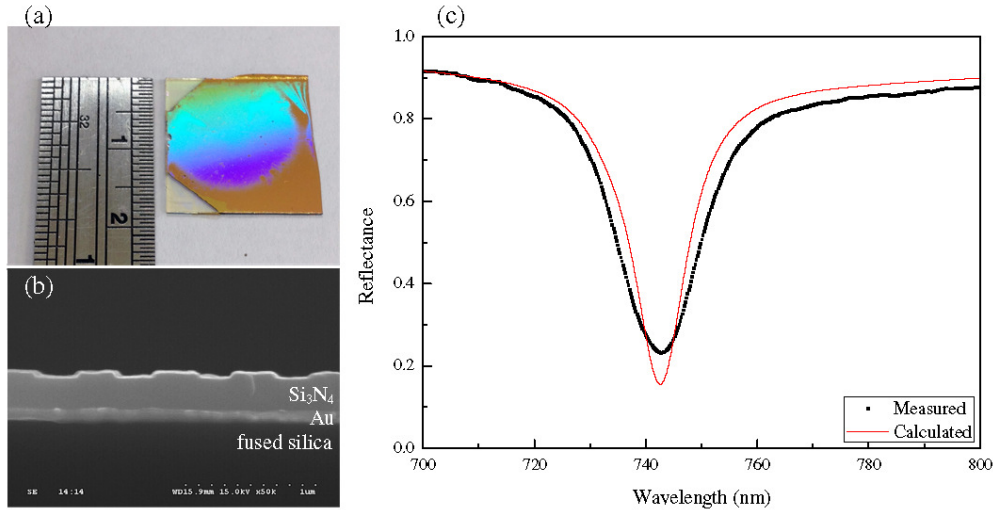


Fig. 7. (a) Photograph of the fabricated MaGMR chip and (b) a cross-sectional SEM micrograph. (c) Measured reflectance spectrum drawn against the computed reflectance spectrum under normal incidence for TM polarization. The structural parameters in the calculation are based on the SEM results which are period: $0.603\mu\text{m}$, waveguide thickness: $0.24\mu\text{m}$, grating depth: $0.04\mu\text{m}$ and filling factor: 0.49.

We further tested the bulk sensitivity by tracking the resonance wavelength in real time. The fabricated chip was sealed into a home-made fluidic cell and a series of sodium chloride solutions with different concentrations were continuously pumped into the cell to produce different bulk background refractive indices. The test solutions were also checked by a commercial refractive index meter. Figure 8(a) shows the real time sensorgram of MaGMR sensor measured under room temperature. The background index varies from 1.3329 to 1.369 and back to 1.3329. As seen in Fig. 8(a), the real time signal is stable and repeatable. With the pure water background the observed resonance wavelength is $0.809\mu\text{m}$; as the background index increases the resonance wavelengths are red-shifted. Figure 8(b) shows the shifts in the resonance wavelength versus the background refractive index. By comparison, a GMR chip resonating around $0.8\mu\text{m}$ in fundamental TM mode was also fabricated and tested. Each result shown in Fig. 8(b) is obtained from 3 independent measurements. The slope of the linear fitting curve stands for the bulk experimental sensitivity S which is 103.29 and 376.78nm/RIU for GMR and MaGMR, respectively. Due to the fabrication error, the sensitivities are slightly varied from simulation results, however, the experiment and simulation results are in the same order and a significant enhancement of sensitivity is obtained by the proposed MaGMR structure. With the same resonance condition, the first diffraction order of grating and the fundamental TM mode at $0.8\mu\text{m}$, MaGMR achieves 264.78% enhancement in sensitivity.

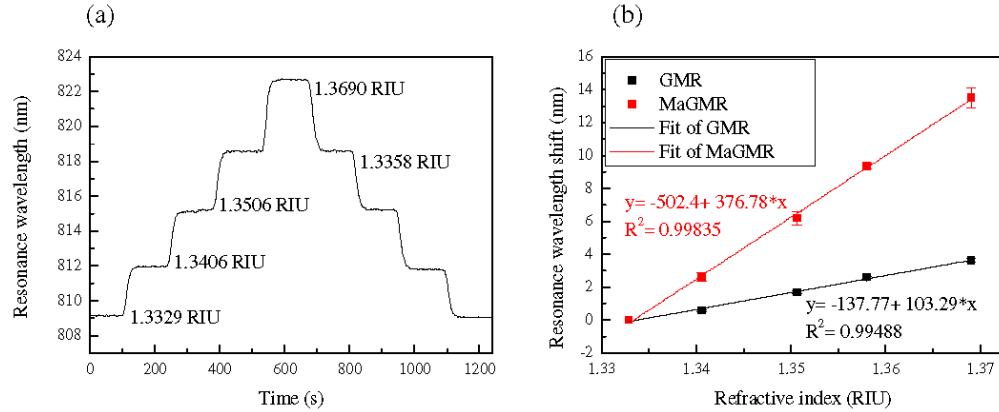


Fig. 8. (a) Real time sensorgram of MaGMR. (b) Resonance wavelength shift of GMR and MaGMR chip, each result is obtained from 3 independent measurements. The slope of the linear fit indicates a bulk sensitivity of 103.29 and 376.78nm/RIU for GMR and MaGMR, respectively.

5. Summary

This paper presents a high sensitivity MaGMR device for bioanalytical applications. The resonance mechanism and its related spectrum results are discussed. The MaGMR structure removes the limitation of the second critical angle, and can be designed to resonate near the most sensitive propagation angle (first critical angle). In the simulation results, the MaGMR structure provides a strongly asymmetric resonance modal profile and the evanescent wave in the top medium is 70.8% of the total resonance energy. A comparison of the MaGMR structure with a typical GMR shows a one-fold enhancement in the evanescent energy in the sensing area, and an enhancement in the sensitivity by 154.8% and 148.9% for the TE and TM modes, respectively. Finally, the highly sensitive performance of the proposed structure is confirmed experimentally. The results of the experiments are in good agreement with the simulation results. The bulk sensitivity achieved in the TM mode is 376.78nm/RIU for a structure resonating at 0.809 μ m with the first diffraction order and fundamental mode.

Acknowledgments

The authors are grateful for the financial support received from the National Science Council of Taiwan, under grant numbers NSC 98-2221-E-008-016-MY2 and NSC 100-2120-M-008-002. The support to the Center for Dynamical Biomarkers and Translational Medicine, National Central University is also acknowledged (NSC 100-2911-I-008-001).