Simultaneous excitation of leaky mode resonance and surface plasmon resonance in tilted fiber Bragg grating

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This paper presents the first work that theoretically demonstrates simultaneous excitation of both enhanced leaky mode resonance (eLMR) and surface plasmon resonance in ultra-thin Au film coated tilted fiber Bragg grating. The mechanism is discussed by investigating the influence of Au film on mode characteristics of leaky modes and guided modes. A stable transmission spectrum that is only composed of strong dense comb-like eLMR in a wide window is realized. The eLMR excited by metal film exhibits insensitive response to external perturbation, which makes it ideal for tunable devices like optical filters and fiber lasers. © 2019 The Japan Society of Applied Physics

Tilting fiber Bragg grating (TFBG) has attracted much attention in telecommunication and sensing fields due to its unique spectral characteristics.1,2 The tilted grating can excite dozens to hundreds of fiber modes to generate dense comb-like resonances that generally correspond to cladding mode resonance (CMR).3,4 At shorter wavelength beyond the CMR bands, leaky mode resonance (LMR) exists, which are characterized by an abrupt decrease in resonance amplitude. The CMR presents sensitive response to external perturbation and can be developed for tunable optical filters.4,5 One of the most widespread studies is to excite surface plasmon resonance (SPR) by coating metal film on TFBG.6,7 Similarly with the Kretschmann configuration,9 the SPR in the TFBG can be excited by cladding guided modes that are phase-matched with surface plasmon polariton in the metal film.9,10 The generation of SPR leads to a strong field localization in the surface of the metal film, which makes the SPR sensitive to the variation of external environment.5,6,10 The polarization dependence of the SPR excited in metal film coated TFBG can be identified by a spectral collapse in the p-polarized CMR spectrum.11,12 However, the influence of the metal film on the LMR (both p- and s-polarized cases) has been widely ignored due to its extremely weak amplitude. Some reports have investigated the sensing performance of the LMR in nano-film coated TFBG, but it is obtained only in high refractive index environment and is still a weak resonance.13-15 More recently, graphene integrated TFBG has been reported to provide a promising approach to greatly enhance the first a few s-polarized LMRs around the cut-off wavelength while the p-polarized counterpart suffers very little variation.16,17 It is also shown that the s-polarized enhanced LMR (eLMR) exhibits advantages over the SPR in terms of sensing performance, indicated by high sensitivity both in air and liquid environment and insensitive wavelength shift.

This work reports simultaneous excitation of both p-s-polarized eLMR and p-polarized SPR in TFBG integrated with ultra-thin Au film. The diagram structure is shown in Fig. 1. The optical fiber is Corning SMF-28e+ single mode fiber that has the same parameters with that in Ref. 16,17. The optical constants of Au film are calculated according to the Lorentz–Drude model.18 The environment is air with surrounding refractive index (SRI) of 1.0. The amplitude of refractive index perturbation is assumed to be $6.0 \times 10^{-4}$. The phase matching condition (PMC) of the tilted grating is given by: $\lambda_{\text{res}} = 2n_{\text{eff}}\Lambda_{\text{s}}/\cos \theta$ for Bragg resonance and $\lambda_{\text{res}} = (n_{\text{eff}}^2 + n_{\text{eff}})\Lambda_{\text{s}}/\cos \theta$ for the $m$th mode resonance in which $n_{\text{eff}}$, $n_{\text{eff}}^2$, $\Lambda_{s} = \Lambda \cos \theta$ and $\theta$ represent respectively effective refractive index of the core guided mode and the $m$th mode, grating period and tilted angle.11 We consider the axial grating period $\Lambda$ of 600 nm and grating length of 20 mm in this work (see Fig. 1). The transmission spectrum of TFBG is simulated utilizing the full-vector complex coupled mode theory.19,20 According to the PMC, the larger the tilted angle is, the higher order modes can be excited for a given TFBG. Consider that the leaky modes correspond to higher order modes, the tilted angle of 24.5° are taken into account and hence a large amount of leaky modes can be excited in this work. As a comparison, the TFBG widely reported in the literature generally corresponds to weakly tilted grating that has tilted angle of $\sim 10^\circ$ and hence only strong comb-like CMR is excited combined with extremely weak LMR.1,6,9

Figure 2 depicts the transmission spectrum of TFBG coated with Au film having different thicknesses. The bare TFBG generates strong comb-like CMR but much weaker LMR in both p- and s-polarized cases. After integration of ultra-thin Au film, however, these two polarized spectra differ greatly in the resonance evolution. As clearly shown, the 2 nm Au film enhances the s-polarized LMR but weakens corresponding CMR. The p-polarized spectrum presents small variation. This situation is very similar with the case where few-layer graphene is considered.16,17 The s-polarized eLMR becomes stronger when Au thickness is increased to 5 nm. Meanwhile, a large decrease in the p-polarized CMR occurs, indicating the metal film becomes thin enough to excite SPR. The further increasing in Au thickness induces much stronger eLMR in a wider window, combined with a clear SPR in p-polarized spectrum. This is totally different from the case in which few-layer graphene excites only s-polarized eLMR.16,17 In particular, the s-polarized eLMR exhibits a strong smooth envelope as Au thickness increases up to 10 nm while 15 nm for the p-polarized eLMR, which...
clearly demonstrates that a strong dense comb-like eLMR is obtained. Note that these two values might not match the exact thickness that induces a smooth envelope when other thicknesses are considered. By this approach, strong p-/s-polarized eLMR in a wide window and p-polarized SPR are generated simultaneously in metal film coated TFBG.

The eLMR and SPR are closely related to the influence of ultra-thin metal film on the mode characteristics. In Fig. 3 is depicted the variation of $n_{\text{eff}}$ and confinement loss at different Au thicknesses. The mode loss is given by $\text{loss} = \left| \text{Im}(n_{\text{eff}}) \right|$ in which $\text{Im}(n_{\text{eff}})$ is the imaginary part of $n_{\text{eff}}$ and $n_{\text{eff}}$. Here the TE/TM modes are taken into account to get a clear comparison. At each Au thickness, the up dotted line represents the TM cladding guided modes at $\text{Re}(n_{\text{eff}}) > \text{SRI}$ and TE guided-like leaky modes at $\text{Re}(n_{\text{eff}}) < \text{SRI}$ while the bottom line corresponds to the TE/TM counterpart (the TE/TM modes can be easily identified by its transverse field profile). The radiation-like leaky modes are not discussed here due to its large $\text{Im}(n_{\text{eff}})$ (in absolute value and similarly hereinafter) and high loss in all cases that lead to ignorable contribution to the mode coupling of TFBG.\(^\text{17}\)

The cladding guided modes of bare TFBG present extremely small $\text{Im}(n_{\text{eff}}) \approx 10^{-15}$, not shown in Fig. 3, combined with very small loss and hence it can fully interact with the core guided mode to generate strong CMR. The $\text{Im}(n_{\text{eff}})$ and loss become much larger for the leaky modes, resulting in very weak LMR. After integrating ultra-thin Au film, the leaky modes become “guided” whereas cladding guided modes begin to be “lossy”. This is clearly evidenced by a large decrease in the $\text{Im}(n_{\text{eff}})$ and loss for the leaky modes and a large increase for the cladding guided modes, as compared with the bare TFBG. However, the $\text{Im}(n_{\text{eff}})$ evolution of TE/TM modes differs from each other. It is clearly shown that the TE leaky modes (bottom line) exhibit a much smaller $\text{Im}(n_{\text{eff}})$ and loss than the corresponding TM counterpart (up line) as Au thickness increases. Meanwhile, the $\text{Im}(n_{\text{eff}})$ and loss of TM guided modes (up line) is slightly larger than the case of TE modes (bottom line). But there is a maximum $\text{Im}(n_{\text{eff}})$ and loss for the TM guided modes (marked by arrows) that are phase-matched with the SPR wave, i.e. the axial component of its propagation constant equals to that of the SPR wave that propagates along the metal film in the axial direction\(^\text{11}\) (see Fig. 1). Consequently, the power carried by the TM guided modes is transferred to the SPR wave, which leads to the generation of SPR. The difference in the evolution of $\text{Im}(n_{\text{eff}})$ and loss between TE and TM guided modes is determined by the polarization dependence of the SPR.\(^\text{12}\) Here the TE/TM guided modes are
polarized in radial/azimuthal direction that is in the $x$–$y$–$z$ plane in the Cartesian coordinate system (see Fig. 1) and hence are $s$–$p$-polarized modes respectively. Therefore, there is a maximum in the variation of $\text{Im}(\eta_{\text{eff}})$ and loss for the TM guided modes, which corresponds to the excitation of the SPR.

It is important to remark that the difference in the eLMR spectrum between the cases of Au film and graphene is essentially determined by optical property of the nano-coating: Au is the material having a low real part of refractive index combined with a very high imaginary component whereas graphene tuned in dielectric state has high both real and imaginary refractive indices. It is this property that induces polarization-dependent influence on the light (generally corresponding to guided fiber modes) propagating through the film coated TFBG. More specifically, the Au film supports the propagation of $p$-polarized light (Au film guided surface plasmon wave) whereas $s$-polarized light (graphene guided surface wave) is propagated in graphene layer.\textsuperscript{1,22} This work further demonstrates that the Au layer supports the propagation of these two polarized leaky modes, clearly evidenced by the great reduction in the $\text{Im}(\eta_{\text{eff}})$ and mode loss, as clearly shown in Fig. 3. This is also verified below by the mode field.

The field profile depicted in Fig. 4 further verifies the excitation of $p$-polarized SPR simultaneously combined with $p$-s-polarized eLMR. Here the field is represented by the intensity distribution defined as $I = 1/2 \text{Re}(e_1 h_x e_y - h_y e_x)$ in which $e$ is the transverse field. The intensity is then normalized to its maximum value. The modes selected here are those modes marked by arrows in Fig. 3. To get a clear observation, two modes including a cladding guided mode and a guided-like leaky mode are considered at each Au thickness. The guided-like leaky mode is randomly selected. The cladding guided mode corresponds to the mode that has the largest $\text{Im}(\eta_{\text{eff}})$ at each Au thickness. As clearly observable, the guided-like leaky mode of bare TFBG has a similar field profile with that of cladding guided mode, except for a large content distributed into external environment due to large loss.\textsuperscript{17} The Au film induces a strong field localization at outside surface of metal film for the TM cladding guided mode, which results from the power transfer from the cladding guided mode to the phase-matched surface plasmon wave.\textsuperscript{19} As a consequence, the SPR is excited in the transmission spectrum. However, the external field content of both TE and TM leaky modes decreases progressively as Au thickness increases. This indicates that the lossy leaky modes become “guided” like the cladding guided modes and then can fully interact with the core guided modes to generate strong eLMR. Compared with Fig. 3, it is therefore clearly shown that the thicker the Au film is (within the thickness range considered in this work), the smaller/larger the $\text{Im}(\eta_{\text{eff}})$ and external field of leaky/guided modes is, and hence the stronger the eLMR/SPR becomes.

Figure 5 shows the spectra response of eLMR/SPR to external perturbation. Two Au thicknesses are considered. The SRI variation is assumed to be $10^{-3}$ that is a very large perturbation in gaseous medium (corresponding to atmospheric pressure increases $\sim$ five times\textsuperscript{23}). The relatively weak eLMR and SPR exhibit insensitive characteristics for 5 nm Au coated TFBG. As the Au thickness increases to 15 nm, a large spectral variation is obtained around the wavelength at which the CMR becomes the eLMR. As observable in the inlets, the first $p$-polarized eLMR shows the highest sensitivity up to 6306dB/RIU while 3073dB/RIU for the most sensitive SPR.\textsuperscript{11} For other eLMRs at shorter wavelength, it is interesting that the spectrum of comb-like eLMRs keep stable, indicated by only $\sim$0.04dB change of the resonance amplitude and unchanged resonance wavelength, when external environment experiences a large variation. The spectral stability means the eLMR is insensitive to external perturbation. This is also clearly demonstrated by the spectrum of $s$-polarized eLMR, which is different from

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**Fig. 4.** (Color online) Field profile of cladding guided modes (up) and guided-like leaky modes (bottom) at Au thickness of (a) 0 nm (bare), (b) 5 nm, (c) 10 nm, and (d) 15 nm. The inlets display two-dimensional (2D) intensity profile of corresponding TM cladding guided modes. The radii of fiber core and cladding are 4.1 $\mu$m and 62.5 $\mu$m, respectively.

**Fig. 5.** (Color online) Spectral response of eLMR/SPR to external perturbation. The inlets depict spectral variation of the first eLMR, other three eLMRs, and the most sensitive SPR, respectively.
environment as Au thickness increases, whereas a strong evidence by the decrease in its mode especially for those away from cladding guided modes. The TE leaky modes present a much smaller \( \text{Im}(n_{\text{eff}}) \) that is \(~10^{-1}\) times smaller than that of TM counterpart. Meanwhile, a large variation around the interface between leaky modes and cladding guided modes is observed. Therefore, the increasing in SRI leads to a large variation in the resonance bands that correspond to the transition from cladding guided modes to leaky modes, but the eLMRs away from the transition position have a stable spectrum (i.e. insensitive response to external perturbation).

By further increasing the tilted angle according to the PMC, the transmission spectrum that consists of only insensitive eLMR can be obtained, as depicted in Fig. 6. The bare TFBG excited strong p-/s-polarized eLMR and p-polarized SPR. The bare TFBG excites extremely weak LMR and CMR.

In conclusion, this work demonstrates that the TFBG integrated with ultra-thin metal film can simultaneously excite strong p-/s-polarized eLMR and p-polarized SPR. Unlike the case of graphene, the Au film decreases greatly the \( \text{Im}(n_{\text{eff}}) \) of p-/s-polarized leaky modes while increases the \( \text{Im}(n_{\text{eff}}) \) of p-polarized cladding guided modes. Meanwhile, the p-/s-polarized leaky modes become more confined, evidenced by the decrease in its mode field in external environment as Au thickness increases, whereas a strong field localization of p-polarized cladding guided modes on the outside surface of metal film is obtained. The eLMR excited by Au film presents insensitive property. By increasing tilted angle of TFBG, a stable transmission spectrum consisting of only strong dense comb-like eLMR is obtained, which is promising for optical filters and fiber lasers.

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