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Whispering gallery mode resonance excitations on a partially gold coated bottle microresonator

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Abstract. The study on the excitations of whispering gallery mode (WGM) resonances optical bottle microresonator (BMR) partially coated with a thin gold Au metal film is presented. The BMR was fabricated through "soften-and-compress" technique on a small section of standard optical fibre. Depositing Au particles on the spheroidal curvature of the BMR surface yields a thin metal-film of a meniscus profile with 200 nm maximum gold thickness and tapered edges. A polarization resolved experimental setup was used to excite TE- and TM-mode resonances. Coupling strengths of the excited WGMs would vary with different coupling arrangements relative to the position of the meniscus Au film. Calculated *Q*-factor values of composite TE and TM mode resonances were determined to be in the range 1800 and 2700, respectively.

1. Introduction

The rich physics of whispering gallery modes (WGMs) which are being offered on optical microcavities and optical microresonators have attracted plenty of interests in the research community in the past few decades, particularly in the field of advanced optoelectronics devices [1,2]. The main attractions of dielectric optical microresonators lies in their ability to confine light with high quality *Q* factor, high finesse but within a small mode volume. Light which are confined on the surface of the microresonators would interact with any bound particles in thousands, millions or billions number of times (depending on the surface roughness) for enhanced light-matter interaction. Among the reported optical WGM microresonators with high finesse and *Q*-factor values is the microsphere [3], microtoroid [4] and microdisc [5]. While the aforementioned microresonators would confine light only along their azimuthal axis, optical bottle microresonators (BMRs) attain the ability to confine light in a 3-dimensional manner along their azimuthal and axial axis [6]. High number of accessible modes are also easily excited due to its spheroidal profile with *Q*-factor values of up to 10^8 [7]. Additionally, optical fibre stems which comes naturally with BMRs adds to their easy-handling and practicality such as for strain sensing applications [8].

In contrast to the superior capabilities of dielectric WGM microresonators, the performance of surface plasmon polarition (SPP) cavities have been previously demonstrated to attain low *Q*-factor values which are mainly due to Ohmic loses in metals [9]. In order to overcome the drawback, a hybrid WGM-plasmonics microresonator was proposed and demonstrated where a high *Q*-factor dielectric microdisc was partially coated with a noble metal [10]. Since then, other types of hybrid WGM-SPP microcavity resonators has been demonstrated as well including microtoroid [11], microcylinder [12] and BMR [13]. In this paper, we present our study on the performance of a hybrid WGM-SPP BMR with a meniscus thin gold (Au) film. Compared to previous hybrid WGM-SPP cavities which attain constant thickness of noble thin metal-film, we report a hybrid BMR with varying thin metal-film thickness and tapered edges covering half of the BMR surface. Q-factor values of composite TE and TM photonics-plasmonics WGM in the range of 1800 and 2700 was calculated, respectively.

2. Experimental Setup

A "soften-and-compress" technique which utilizes an optical fusion splicer was applied on a small section of a continuous commercial single-mode fibre (SMF) in order to generate the spheroidal profile of the BMR [14]. The fabricated BMR attains bottle diameter of ~ 180 μm, neck-to-neck length of ~ 400 μm and fibre stem diameters of 125 μm. For SPPs generation, the BMR was then coated with a thin layer of Au film through metal-evaporation process. The metal deposition process evaporates Au particles from bottom to the top (where the BMR was fixed) in a controlled vacuum chamber system. The combination of this metal deposition process with BMR surface curvature ensures that only half of the BMR surface would be coated with the thin Au-film along with a meniscus profile and tapered edges, as shown in figure 1 (a). The maximum thickness of the Au film on the BMR was measured to be 200 nm. The exposed dielectric part of the hybrid plasmonic bottle microresonator (PBMR) is crucial for light coupling processes.

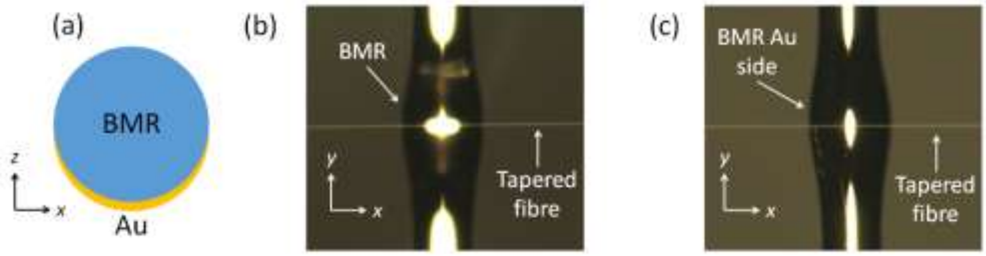

Figure 1. (a) Cross-section schematic diagram of Au metal-film with a meniscus profile on BMR surface, (b) image of the BMR coupled with a tapered optical fibre on the dielectric side and (c) Au coated side

To excite WGMs and SPPs of the hybrid microresonator, tapered optical fibre with 2 μm waist diameter and an adiabatic profile was used to evanescently coupled lasing light into the dielectric part of the microcavity [15]. A polarization-resolved experimental setup which incorporates free-space optics was used to characterize the hybrid PBMR [16]. The PBMR was positioned on precise optical fibre rotating mounts on its two sides by firmly clamping the fibre stems. The rotating mounts was secured on top of two optical table micro-stages for practical handling of the microresonator. The rotating mounts were utilized in order to precisely determine the angle of rotation of the PBMR so that varying tapered fibre coupling arrangements relative to the thickness of the Au would occur. Lasing light with fixed power of – 7 dBm was launched into the SMF between 1520 – 1530 nm wavelength by using a tunable laser source (TLS) (Agilent 81600B). The loss of the free-space optics was determined to be < 8 dB during the entire experimental procedure. The polarization of the input light was tuned by using an optical fibre polarization controller (PC) and the polarization state of the coupled light was determined by a using a high extinction ratio (> 45 dB) polarizer lens. The polarizer lens was placed in a precise rotation mount for straightforward 0° (TM) and 90° (TE) rotation. The other end of the SMF was then spliced to an adiabatic tapered optical fibre with its waist section being placed on top of and in contact with the PBMR. For precise coupling arrangements, the tapered optical fibre was fixed on an optical micro-stage during the entire experimental procedure. The other end of the tapered fibre was cleaved at its full 125 μm diameter for free-space output light collection. An objective lens L1 was brought close to the cleaved optical fibre in order to collimate the output light and to guide it to pass through the polarizer lens for the input light polarization tuning process. The polarized light was then focused down by another objective lens L2 into a multimode optical fibre (MMF). The other end of the MMF was connected to a high sensitivity (-80 dBm to + 10 dBm) optical power meter (Agilent 81635A) for the output light collection. To attain precise TE- and TM-excited modes, a sharp contrast between the resonances was determined during the polarization tuning process.

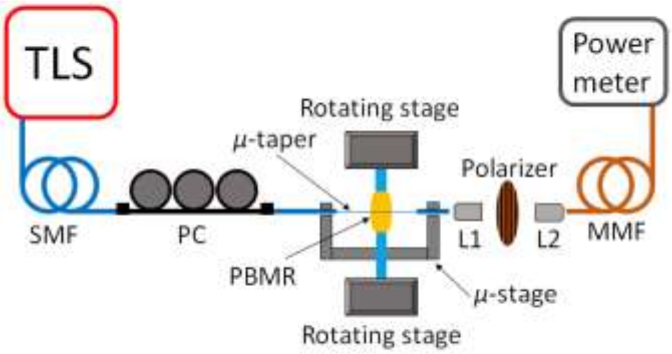

Figure 2. Polarization-resolved experimental setup

3. Results and Discussion

The output transmitted spectra of the PBMR resonances with various coupling arrangement is shown in figure 3. Each dip in the spectrum represents either a single resonance or resonances of a family group-mode. From the output spectrum, the free spectral range of the PBMR was measured to be ~ 3.0 nm. For TE excited WGMs, two specific resonances, G (green dashed-line) and H (blue dashed-line), were monitored during the experiment. The rotation of the BMR θ_{BMR} was first set to be at 0° angle relative to the position of the tapered optical fibre (which is the furthest from the thickest part of the Au film). Resonance G and H were first measured to attain similar coupling strength in the range of 6 dB with such coupling arrangement. With $\theta_{BMR} = 23°$, the coupling strength of resonance G became weaker to ~ 4 dB while the coupling strength of resonance H increased to ~ 8 dB. Interestingly, with $\theta_{BMR} = 113°$, many other distinguishable resonance dips appeared with neither resonance G nor H attaining the highest coupling strength. Placing the tapered fibre on the Au coated part of the PBMR would not couple any light into the microcavity and all of the launched power would pass through the tapered fibre, as could be seen with coupling arrangement $\theta_{BMR} = 180°$. Low coupling strength of resonance G and H were observed with $\theta_{BMR} = 315°$ with many other weak resonance dips throughout the spectrum wavelength.

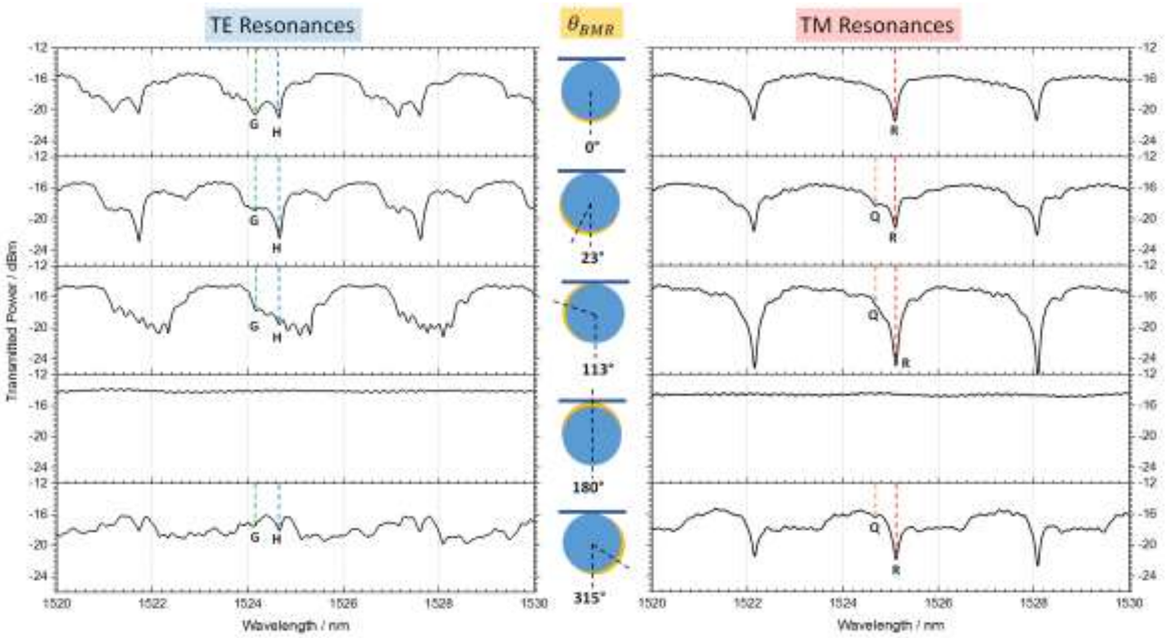

Figure 3. TE and TM output transmission spectrum of the hybrid PMBR with various tapered fibre coupling arrangements θ_{BMR}

It should be stressed that since SPPs are transverse magnetic in nature, TM-polarized light are required to excite plasmonics wave on any noble metal surface. With TM-polarized light launched into the cavity of the PBMR, two main resonances, Q (orange dashed-line) and R (red dashed-line) were monitored with various coupling arrangements. With $\theta_{BMR} = 0°$, only resonance R was observed on the output spectrum with ~ 8 dB coupling strength. Resonance Q only weakly appeared with $\theta_{BMR} = 23°$ while resonance R coupling strength weakens. Strong and distinguishable TM-polarized R resonances were generated with $\theta_{BMR} = 113°$ with coupling strength of > 10 dB along with weak Q resonances. This would be the most promising coupling arrangement to study upon for an enhanced plasmonics wave generation on a BMR. As with the previous observations, no light was coupled into the cavity of the PBMR with $\theta_{BMR} = 180°$ and resonances with moderate coupling strength were generated with $\theta_{BMR} = 315°$. For TM excited resonances, the highest composite Q-factor value calculated $(Q = \lambda/\Delta\lambda)$ was in the range of 2700 at $\theta_{BMR} = 113°$ and for TE excited resonances, the highest composite Q-factor value calculated was in the range of 1800 at $\theta_{BMR} = 23°$.

From the recorded output spectrum, it could be stated that TE- and TM-resonances of the PBMR would vary with different coupling arrangements of the tapered fibre relative to the position of the meniscus thin metal-film. To gain better insight of the obtained result, Lorentzian fittings were performed using Origin computer software on the output spectrum with $\theta_{BMR} = 113°$, where most of the TE resonances appeared and strongest coupling efficiencies of TM resonances were observed. As shown in figure 4, in order to obtain the most accurate fitting, the cumulative fit peak (cyan solid line) of the Lorentzian must be as matching as possible with the real measured spectrum (black solid line). With TE-polarized input light, eight main individual resonances were observed within the family group-mode centring at 1522 nm. However, due to vernier effects, only seven main resonances were observed at family group-mode centring at 1525 and 1528 nm. The resonances of the longer wavelengths in these family group-modes were very closely excited to one another resulting them to be indistinguishable in the fitting. Lorentzian fitting on the TM-polarized output spectrum yields three main resonances with one weak resonance (orange solid line) appearing on the shorter wavelength of the family group-mode. At family group-mode centring 1528 nm, this weak resonance could not be fitted using the software as the vernier effect shown by the measured spectrum (solid black line) has separate it to even weaker resonances with weak resonance dips. The strongest resonance (resonance R) presented by the red solid line attain the highest coupling efficiency of < 9 dB, slightly lower than the maximum reached dip. The reason for this lower coupling strength fitting is because multiple resonance dips comprising of individual resonances (as in the actual family group-mode measured data) would slightly lower the output power at a specific resonance dip which makes an individual resonance appearing to attain higher coupling efficiency.

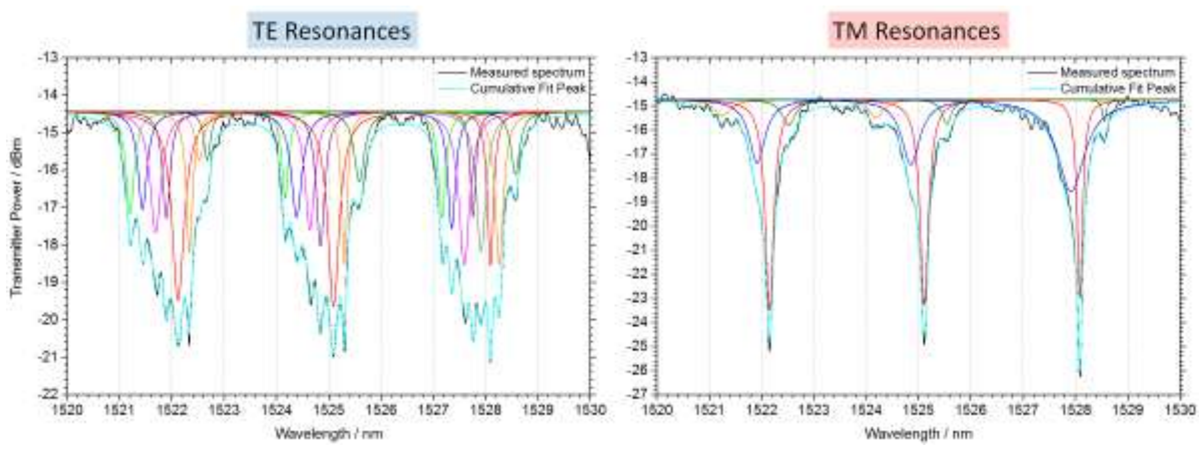

Figure 4. Measured spectrum, Lorentzian fittings and cumulative fit peak of TE and TM mode resonances of the PBMR output transmission spectrum with fixed coupling arrangements $\theta_{BMR} = 113°$

4. Conclusion

In summary, excitation of WGM-SPP resonances utilizing an optical BMR has been successfully demonstrated. The proposed hybrid PBMR attains a thin meniscus Au metal-film of 200 nm maximum thickness along with tapered edges. Different coupling arrangements of the tapered fibre relative to the position of the meniscus Au film could be realized with different θ_{BMR} performed. Coupling strengths of the excited resonances would vary with different coupling arrangements both for TE- and TM-excited resonances. Lorentzian fitting reveals that TE and TM excited resonances actually comprise of eight and three main individual resonances, respectively. Composite resonances Q-factor value was calculated to be in the range of 1800 for TE- and 2700 for TM-mode resonances. The varying excitation strengths of the proposed hybrid PBMR resonances would be beneficial for future applications of optoelectronics plasmonics devices.

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