Resonant Cavity Enhanced Silicon Photodetector Integrated to a Fiber Optic Coupler

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ABSTRACT

Morphology dependent resonances of dielectric microspheres are used for polarization insensitive optical channel dropping from an optical fiber half coupler to a silicon photodetector in the M-band. The dropped channels are observed in the elastic scattering and the transmission spectra. The highest quality factor morphology dependent resonances have a repetitive channel separation of 0.14 nm and a linewidth of 0.06 nm. The filter drops approximately 10% (0.5 dB) of the power at the resonance wavelength. The power detected by the photodiode is estimated to be approximately 3.5% of the power in the fiber.

Keywords: Microsphere, microcavity, light coupling, optical fiber half coupler, generalized Lorenz-Mie theory.

1. INTRODUCTION

Optical microsphere resonators have been recently utilized in quantum optics, laser science, spectroscopy, and optoelectronics and attracted increasing interest due to their unique optical properties. Microspheres possess high quality factor (Q-factor) optical morphology dependent resonances, and have small volumes. Optical microsphere resonators have recently attracted an increasing interest in quantum optics, laser science, spectroscopy, biosensor technology, and optoelectronics. Microspheres possess high quality factor (Q-factor) optical morphology dependent resonances (MDR's) and have relatively small volumes [1, 2]. Q-factor gives information about the lifetime and linewidth of a MDR. These tiny optical cavities, whose diameters may vary from a few to several hundred micrometers, have MDR's with reported Q-factors as large as 3×10^9 [3]. There has been extensive research on the MDR's, which are also called whispering gallery modes (WGM's): low threshold lasing from Nd-doped silica microspheres [4], polymer microsphere lasers [5] and, Raman microsphere lasers [6] have been demonstrated. Additionally, strain tunable microsphere oscillators [7], add-drop filters [8] have been realized. Thermo-optical switching [9] can also be applied to microspheres for frequency control in optical communication applications. Due to their great sensitivity, MDR's of microspheres are also considered for biosensor applications [10].

Microsphere resonators are uniquely applicable in compact optoelectronic devices for wavelength division multiplexing (WDM) applications [11]. In optical communication, WDM is important for increasing the bandwidth of the current fiber optic networks. In WDM, the final optical to electronic conversion needs an all-optical packet-switching layer, which consists of all-optical gates, interferometers, semiconductor optical amplifiers, resonant cavity enhanced photodetectors, optical random access memory elements, and channel dropping filters. In these planar lightwave circuits, dielectric microspheres with their MDR's, can be used as compact channel dropping filters.

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In this paper, we report for the first time to our knowledge the channel dropping of light in an optical fiber using a dielectric microsphere integrated with a silicon photodetector. The detection of MDR's is performed by using a windowless wide area silicon photodiode in proximity to the microsphere, which is placed on an optical fiber half coupler (OFHC). The MDR's in the elastic scattering spectrum and associated dips in the transmission spectrum are experimentally observed. This coupling geometry is suitable for the manufacturing of polarization-independent integrated optoelectronic devices for optical communications.

2. MORPHOLOGY DEPENDENT RESONANCES

The MDR's of a microsphere are analyzed by the localization principle [12] and the generalized Lorenz-Mie theory (GLMT) [13, 14, 15]. Each MDR is characterized by a mode number n and a mode order l . The mode number n gives the number of maxima between 0° and 180° degrees in the angular distribution of the energy of the MDR. The radial mode order l indicates the number of maxima in the internal electric field distribution in the radial direction. As the mode order increases, number of peaks in the internal intensity profile increases, corresponding to the mode order, and the highest peak is located at the most inner side in the radial direction.

Efficient coupling to MDR's requires great attention for most of the applications. Efficient coupling to MDR's requires both the adjustment of the frequency of the excitation beam to a MDR and matching of the angular momentum of the excitation beam with the angular momentum of the MDR. This last condition is not met with a free propagating (plane-wave) beam, even if it is focused near the edge of the microsphere [2, 7, 16]. Evanescent coupling with a resonant off-axis Gaussian beam provides efficient excitation of the MDR's of a microsphere more uniformly and more efficiently than does a plane wave [11]. Such coupling has been implemented, by the use of thin tapered optical fibers, planar waveguide couplers, side-polished optical fibers, or high-index-prisms. If a microsphere is placed near the angled surface, and within the evanescent field of the fiber-optic core, then there is an efficient energy exchange in resonance between the waveguide mode of the fiber and the MDR of the microsphere [17].

3. EXPERIMENTAL SETUP

Figure 1. The schematic of the experimental setup of the optical channel dropping filter detector.

A schematic of the experimental setup is shown in Fig. 1. A common approach to excite MDR's is to use an optical fiber half coupler (OFHC), which is produced by polishing down the cladding of an optical fiber to the point, where the evanescent field is locally exposed [18]. In the experiment, the OFHC is fabricated from a 810 nm single mode fiber with a core radius of $1.9\text{ }\mu\text{m}$ and a refractive index of 1.462, and a cladding radius of $62.5\text{ }\mu\text{m}$ with refractive index of 1.457, which is laid on a glass substrate with a low curvature. The cladding of the fiber below the microsphere is shaved down to $0.7\text{ }\mu\text{m}$ in order to approach the core of the fiber. This excitation geometry effectively becomes the optical equivalent of a Gaussian beam with an infinite skirt length passing near the microsphere. The transmission loss from the OFHC is corresponding to 21 dB (0.8%). The microsphere used in the experiment is a BK7 type glass with a radius $a = 500\text{ }\mu\text{m}$ and a refractive index of 1.502. MDR's of the microsphere are excited by using a tunable distributed feedback (DFB) semiconductor laser. Wavelength tuning is achieved by tuning the temperature of the DFB with a laser diode controller. The elastically scattered polarization-independent light at 90° is detected by using an unamplified windowless wide area ($4\text{ mm} \times 4\text{ mm}$) silicon photodiode placed approximately 1 mm away from the microsphere-OFHC system as seen in Fig. 2. The photodetector signal is sent to a digital oscilloscope for monitoring and data acquisition. The optical power and the wavelength of the transmitted light are measured by an optical multimeter (OMM) with a silicon power/wave head. Device controls and data acquisition are performed with the IEEE-488 standard GPIB interface.

Figure 2. The side view picture of the optical fiber coupler, the microsphere, and the silicon detector.

4. ELASTIC LIGHT SCATTERING

Fig. 3 shows the elastic scattering and the power transmission spectra. MDR's in the elastic scattering and the associated dips in the transmitted power spectra are clearly observed. The temperature of the DFB laser is tuned between $19\text{ }^\circ\text{C}$ and $30\text{ }^\circ\text{C}$ at a constant current of 31.2 mA. This temperature range corresponds to a wavelength range from 811.83 nm to 812.32 nm. At the MDR wavelengths, the laser is coupled out of the fiber into the microsphere, which results in dips in the transmitted signal. It is important to note that the fractional depth of the dips in the transmission spectra is not the same for all MDR's. This is due to different Q-factors and coupling efficiencies of the MDR's.

As shown in Fig. 3, the power coupled into MDR's was estimated from the power transmission spectra. For example, the MDR at 812.09 nm has a transmitted power of 67 μW . When the microsphere is not present, the transmitted power is estimated to be approximately 75 μW . Therefore, the power coupled (P_i) into the MDR is approximately 8 μW , which corresponds to a 0.5 dB (10%) loss in the transmission. For the experimental parameters of ω_0 , beam waist half width, = 2 μm , $\lambda=812.09$ nm, the elastically scattered intensity I_i is calculated as 2 kW/cm^2 using $I_i = P_i / \sigma$, where the scattering cross section of the mode is defined as σ . Using the experimental parameters, the coupling efficiency of a Gaussian beam ($\langle \sigma \rangle$) into MDR's is estimated to be 5.3% for the system, which correlates well with the measured 10% coupling efficiency. Since the large area silicon photodiode has dimensions of 4 x 4 mm, the approximate power transfer efficiency of the microsphere to the detector can be estimated as $(\theta / \pi) \times 10\% = 3.5\%$, where θ is the angle covered by the photodiode (see Fig.2).

Figure 3. The elastic scattering intensity and the power transmission spectra from the glass microsphere.

The scattered signal intensity increases with the decreasing the distance of the photodiode to the microsphere. There is a background due to the OFC surface imperfections [19]. With a larger refractive index or smaller size microsphere, the MDR peaks would be more clearly observable in the spectrum.

The bandwidths of the MDR's are measured to be 0.05 nm and the separation between the same mode order (l) MDR's with consecutive mode numbers (n), $\Delta\lambda$, is measured to be about 0.14 nm, which is consistent with the calculation based on the Mie scattering theory [20].

The measured quality (Q) factor of the MDR's in the polarization-independent scattering spectrum is approximately of 10^4 . The high Q factor MDR's are superimposed upon a background of low Q -factor MDR's. Since no polarizer is used in the experiment, the spectrum gets contributions from both the TE and the TM modes, resulting in spectrally merged MDR's.

In practice, absorption, scattering on defects [17], scattering on impurities, residual surface roughness [21] are responsible for the measured losses corresponding to Q-factors due to the presence of small shape distortions, and surface irregularities of the particle. The observed Q-values should be compared with the values determined by $Q^{-1} = Q_{\text{abs}}^{-1} + Q_s^{-1} + Q_r^{-1}$, where Q_r^{-1} corresponds to the intrinsic diffraction leakage, and Q_s^{-1} describes the losses due to light scattering by surface roughness and Rayleigh scattering inside the sphere. The optical absorption loss is expressed as $Q_{\text{abs}}^{-1} = \alpha \lambda / 2\pi m$ with the absorption coefficient of α . The presence of surface roughness and the molecular roughness would give higher-Q MDR's [22], when the beam is aimed slightly inside the sphere's rim [16].

5. CONCLUSIONS

In conclusion, detection of MDR's is achieved by using a silicon photodiode in close proximity to the microsphere and OFHC. The dropped channels are observed in the elastic scattering and the transmission spectra. The highest quality factor morphology dependent resonances have a repetitive channel separation of 0.14 nm and a linewidth of 0.06 nm. The OFHC, microsphere, and photodiode system can be considered as a prototype of an integrated channel-dropping filter detector. With the proper system design and optimization, it would be possible to totally drop the selected MDR's power from the transmission spectrum.

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