Microsphere based Resonant Cavity Silicon Photodetector

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ABSTRACT

Dielectric microspheres are used to resonantly couple light from a half optical fiber coupler to a large area silicon photodetector. Dielectric microspheres possess high quality factor morphology dependent resonances, i.e., whispering gallery modes. The observed resonances have a channel spacing of 0.14 nm and a linewidth of 0.06 nm. These resonances provide the necessary narrow linewidths that are needed for high resolution optical spectroscopy applications. Optical communication applications of this system are studied experimentally and theoretically.

Keywords: Channel dropping filter, dielectric microsphere, evanescent coupling, integrated optoelectronics, microsphere resonator, morphology dependent resonances, optical resonance, optical coupler, optical fiber, silicon photodetector, whispering gallery modes.

1. INTRODUCTION

Dielectric microspheres have found various photonic applications¹. Morphology dependent resonances (MDR's) or alternatively whispering gallery modes (WGM's) of dielectric microspheres provide the necessary optical feedback for applications in spectroscopy, laser science, and optical communications. Among these applications are novel microlasers, optical couplers, and optical filters.² Low threshold lasing from Nd-doped silica microspheres², polymer microsphere lasers³ and Raman lasers have been demonstrated. Strain tunable microsphere oscillators⁴, add-drop filters⁵, and thermo-optical switching⁶ have been realized for the frequency control in optical communications.

Microsphere resonators are uniquely applicable in compact optoelectronic devices in wavelength division multiplexing (WDM) applications.⁷ WDM has the advantage of 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 (RCE) photodetectors, optical random access memory (RAM) elements, and channel dropping filters. In these planar lightwave circuits, dielectric microspheres can be used as compact channel dropping filters.

In this paper, we report the optical channel dropping through an optical fiber coupler using a dielectric microsphere integrated to a large area silicon photodetector. The detection of the MDR's is performed by using a windowless wide area silicon photodiode placed in close proximity to the microsphere. The microsphere itself is placed on an optical fiber half coupler (OFHC).⁸ 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 silicon based polarization-independent integrated optoelectronic devices for optical communications.⁹ Additionally, polarization control can be achieved by placing a polarizer in front of the large area silicon photodetector.

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2. MORPHOLOGY DEPENDENT RESONANCES

The MDR's of the microsphere can be understood using geometrical optics. As the light propagates around the microsphere, it is confined by almost total internal reflection (TIR).¹⁰ After circumnavigating the microsphere, the light wave returns to the original starting point in phase to interfere constructively with itself. This constructive interference can occur only at certain discrete MDR wavelengths.¹¹

Each MDR is characterized by a mode number (n) and a mode order (l). Physically, (n) indicates the number of nodes in the internal intensity distribution as the polar angle is varied from 0° to 180° . The mode order (l) indicates the number of nodes in the internal intensity distribution in the radial direction. For each set of mode number (n) and mode order (l), there is a transverse electric (TE) and transverse magnetic (TM) MDR. For a given microsphere, the MDR occurs at specific value of the size parameter, $x_{n,l}$, which is given by $2\pi a/\lambda_{n,l}$, where $\lambda_{n,l}$ is the light wavelength in vacuum and a is the radius of the microsphere. These MDR's have been verified experimentally at optical wavelengths with micrometer-sized spheres.

The greatest impediment to the use of microsphere resonators in practical devices has been the difficulty of efficiently light coupling into and out of the spheres. To couple light into or out of the microsphere, it is necessary to overlap the evanescent field of the MDR with the evanescent field of the TIR. 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.¹²

3. EXPERIMENTAL SETUP

A common approach is to polish down the cladding of an optical fiber to the point, where the evanescent field is locally exposed.¹³ In the experiment, the OFHC is fabricated from a 810 nm single mode fiber with a core radius of $1.9 \mu\text{m}$ and a refractive index of 1.462, and a cladding radius of $62.5 \mu\text{m}$ 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 $0.7 \mu\text{m}$ 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 corresponds to 0.8%.

Figure 1. (a) The schematic and (b) the photograph of the optical fiber half coupler together with the glass microsphere.

A schematic and a photograph of the optical fiber half coupler (OFHC) together with the glass microsphere are shown in Fig. 1. The microsphere used in the experiment is a BK7 type glass with a radius $a = 500 \mu\text{m}$ 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 mm x 4 mm) silicon photodiode placed approximately 2 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. (a) The photograph and (b) the schematic of the side view picture of the optical fiber half coupler, the microsphere, and the large area silicon photodetector.

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°C and 30°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.

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 OFHC surface imperfections.¹⁴ 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 given by $\Delta\lambda = (\lambda^2 \arctan(m^2-1)^{1/2}) / (2 \pi a(m^2-1)^{1/2})$.¹⁵ 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.

5. THEORETICAL RESULTS

For telecom applications of high channel counts, linewidths in the order of several GHz and channel spacing of several THz are necessary. Microspheres can be tailored to enable required channel spacing and linewidths. Factors influencing the MDR's are mainly size and refractive index of microspheres. To implement these criteria, we have also theoretically analyzed the MDR spectra of small glass microspheres in the C-band.

Figure 4. Calculated (a) TE and (b) TM mode numbers (n) and mode orders (l) of the BK7 glass microsphere ($a = 30 \mu\text{m}$, $n = 1.50$) between 1530 nm and 1565 nm.

Generalized Lorenz-Mie theory (GLMT), which is a direct extension of the plane-wave Lorenz-Mie theory, describes the elastic scattering of an arbitrary light beam by a spherical particle.¹⁶ For the calculations of both TE and TM elastic scattering spectra, a Gaussian beam (with an infinite skirt length and beam waist with a half-width of $2 \mu\text{m}$) propagating just at the edge of the microsphere is used at a scattering angle of 90° .¹⁷ In Fig. 4(a) and (b), the mode order (l) and the mode number (n) are calculated for both TE and TM MDR's at a wavelength range between 1530 nm and 1565 nm corresponding to C-band for a BK7 glass microsphere with the radius of $a = 30 \mu\text{m}$ and a refractive index of $m = 1.50$, respectively. Based on the Lorenz-Mie theory, the separation between the adjacent peak wavelengths of the same mode order (l) MDR's with subsequent mode numbers (n), the mode spacing $\Delta\lambda$ of the MDR's with the identical mode order (l) and consecutive mode number (n) is calculated to be 9.35 nm, which agrees well with $\Delta\lambda = (\lambda^2 \arctan(m^2-1)^{1/2}) / (2 \pi a(m^2-1)^{1/2})$.

6. CONCLUSIONS

We have demonstrated the excitation of MDR's of glass microspheres using an optical fiber half coupler (OFHC) and, a temperature tunable distributed feedback (DFB) laser. MDR peaks in the elastic scattering spectra and associated dips in the transmission spectra are observed experimentally. With the proper system design, it would be possible to totally drop the selected MDR's power from the transmission spectrum. Simulation results of elastic scattering spectra of glass microspheres in the C-band for data transmission are presented. The detection of MDR's is achieved by using a silicon photodiode in close proximity to the microsphere and OFHC. The OFHC, microsphere, and photodiode system can be considered as a prototype of an integrated channel-dropping filter detector.

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