Semiconductor and Dielectric Microsphere based Channel Dropping Filters and Detectors

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ABSTRACT

Dielectric and semiconductor microspheres coupled to optical fibers are used for optical channel dropping in the infrared communication wavelengths of 810 and 1300 nm. Additionally, a dielectric microsphere coupled to an optical fiber and placed in close proximity to a silicon photodiode is used for resonant detection of communication signals at 810 nm. The observed resonances have quality factors of 100,000. The measured quality factors are limited by the sensitivity of the measurement setup. These optical resonances provide the necessary narrow linewidths that are needed for high resolution optical communication applications. The microsphere, optical fiber, and detector system shows promise as a building block for optoelectronic integration.

Keywords: Channel dropping, microsphere, evanescent coupling, integrated optoelectronics, resonator, morphology dependent resonances, optical resonance, optical coupler, optical fiber, 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 silicon μ -sphere based optical channel dropping. The MDR's in the elastic spectrum and associated dips in the transmission spectrum are experimentally observed by coupling of light between an optical fiber half coupler (OFHC) and the MDR's of a silicon μ -sphere placed on the OFHC surface. Silicon μ -spheres with their MDR's and Q-factor of 10^5 can be used as active channel-dropping filters.

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We are also reporting on 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.⁹ This coupling geometry is suitable for the manufacturing of silicon based polarization-independent integrated optoelectronic devices for optical communications.¹⁰ Additionally, polarization control can be achieved by placing a polarizer in front of the large area silicon photodetector.

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).¹¹ 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.¹²

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.¹³

3. SILICON MICROSPHERE FOR OPTICAL CHANNEL DROPPING

Silicon has been the material of choice for the electronics industry for more than half-a-century. It is a relatively inexpensive, plentiful, and well understood material for producing electronic devices [14]. Additionally, the need for low cost photonic devices has stimulated a significant amount of research in silicon photonics [15]. Although silicon photonics is less well developed as compared to III-V technologies; it is poised to make a serious impact on the telecommunications industry, as well as in many other photonic applications. Recent studies show that the silicon will be widely used, as in electronics, in the photonics industry [16]. Silicon microspheres (μ -spheres) with their morphology dependent resonances (MDR's) will be an additional step for the use of silicon in optical communication applications. Silicon is transparent in the optical communication bands that also make silicon the material of choice for photonics.

The schematic of the experimental setup is shown in Fig. 1. A tunable distributed feedback (DFB) laser is used to excite the MDR's of the silicon μ -sphere. Wavelength tuning is achieved by tuning the temperature of the DFB laser with a laser diode controller (LDC). Laser light is coupled into the OFHC. The optical fiber used in the OFHC is a standard 1300nm single-mode fiber. The silicon μ -sphere used in the experiment with $a = 530 \mu\text{m}$ and $n = 3.5$ is placed on the interaction region of the OFHC (Fig. 2). The scattered light from the microsphere at 90° is collected by a microscope lens is measured by an InGaAs photodiode. The transmitted power through the optical fiber is measured by an optical multimeter (OMM) with InGaAs power/wave head (PWH). The InGaAs photodiode signal is sent to the digital oscilloscope for signal monitoring and data acquisition. An infrared viewer is used to observe scattered light from the μ -sphere. Data acquisition and control are performed with IEEE-488 GPIB interface.

Fig. 1. Schematic of the experimental setup.

Fig. 2. Picture of the OFHC, silicon μ -sphere, and microscope objective.

Fig. 3 shows the elastic scattering spectrum at a scattering angle of 90° from the silicon μ -sphere and the power transmission spectra at the end of the optical fiber. There is a background due to OFHC surface imperfections. The temperature of the DFB laser is tuned from 18°C to 34°C at a constant current of 29 mA. The temperature range corresponds to 1302.18 nm to 1303.30 nm. The dips in the transmitted signals are due to the coupling to the MDR's of the μ -sphere.

Fig. 3. Elastic scattering spectrum and power transmission spectrum from the silicon μ -sphere.

The mode spacing $\Delta\lambda$, i.e. wavelength difference between consecutive mode numbers in the same mode order, is measured to be 0.19 nm. The linewidths $\delta\lambda$ of the MDR's are measured to be 0.007 nm, which results in a quality factor ($Q = \lambda/\delta\lambda$) of approximately 10^5 .

4. INTEGRATED MICROSPHERE AND SILICON DETECTOR

In this part of the experiment, the OFHC¹⁷ is fabricated from an 810 nm single mode fiber with a core radius of 1.9 μm and a refractive index of 1.462, and a cladding radius of 62.5 μm 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 μm 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 4. The photograph of the optical fiber half coupler together with the glass microsphere.

A photograph of the optical fiber half coupler (OFHC) together with the glass microsphere are shown in Fig. 5. 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. 5. 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 5. The photograph of the side view picture of the optical fiber half coupler, the microsphere, and the large area silicon photodetector.

Fig. 6 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 6. 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.¹⁸ 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 $\Delta\lambda = (\lambda^2 \arctan(m^2-1)^{1/2}) / (2 \pi a(m^2-1)^{1/2})$.¹⁹ 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. CONCLUSIONS

We have demonstrated the excitation of MDR's of silicon and 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. The microsphere, optical fiber, and detector system shows promise as a building block for optoelectronic integration.

6. ACKNOWLEDGMENTS

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