Morphology-dependent resonances of optical microsphere resonators for the realization of passive wavelength-division multiplexing components

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Abstract. Morphology-dependent resonances of microspheres can provide the necessary optical feedback for applications in spectroscopy, laser science, and optical communications. The elastic scattering of focused light from dielectric microspheres is understood by the localization principle and the generalized Lorenz-Mie theory. We excited the morphology-dependent resonances of glass microspheres by a tunable distributed-feedback laser and detected the elastically scattered signal. Efficient coupling to morphology-dependent resonances is achieved using an optical fiber half coupler. Resonance peaks in the elastic scattering spectra and associated dips in the transmission spectra are observed experimentally. Simulation results of elastic scattering spectra of glass microspheres in the C-band are presented. © 2004 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.1689332]

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1 Introduction

Optical microsphere resonators have found various applications in quantum optics, laser science, spectroscopy, and optoelectronics.¹ Microspheres possess high-quality-factor (Q -factor) optical morphology-dependent resonances (MDRs) and have relatively small volumes.² These tiny optical cavities, whose diameters may vary from a few to several hundred micrometers, have MDRs with reported Q -factors as large³ as 3×10^9 . Low-threshold lasing in Nd-doped silica,⁴ polymer,⁵ and Raman active media⁶ have been demonstrated using microspheres. MDRs of dielectric microspheres provide the necessary optical feedback for applications in optical communications, such as optical couplers, optical amplifiers, and optical filters. Strain tunable microsphere oscillators,⁷ add-drop filters,⁸ and thermo-optical switching in μ -spheres⁹ have also been realized for filtering, multiplexing, and switching applications.

Microspheres are uniquely applicable in compact optoelectronic devices for wavelength-division multiplexing (WDM) applications. In optical communication, WDM offers a scalable solution for using existing fiber optic networks to gain increased bandwidth. More channels with reduced channel spacing are possible with dense WDM (DWDM) technology. In these lightwave circuits, dielectric

microspheres can be used to develop WDM and DWDM components, which support narrow channel spacing, high channel counts, and the addition and the dropping of a large number of wavelengths.

In this paper, MDRs are characterized experimentally by evanescently coupling light along an optical fiber half coupler (OFHC) into glass microspheres. We also analyzed the MDR spectra of solid microspheres in the C-band for possible WDM and DWDM applications.

2 MDRs

The MDRs of the μ -sphere can be explained as follows: as the light propagates around the inside surface of the μ -sphere, it undergoes an almost total internal reflection¹⁰ (TIR). The rays of the MDR have the property that all subsequent bounces have the same angle of incidence. After circumnavigating the μ -sphere, the light wave returns to the starting point in phase to interfere constructively with itself. This constructive interference can occur only at certain discrete MDR wavelengths.¹¹ Hence, the light is confined to a band within the great circle of the μ -sphere. 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 deg. The mode order l indicates the number of nodes in the internal intensity distribution in the radial direction.¹² For each set of mode numbers,¹³ there is a transverse electric (TE) and transverse magnetic (TM) MDR. For a given μ -sphere, the MDR occurs at a specific value of the size parameter, $x_{n,l}$, which is given by

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Fig. 1 Schematic of the experimental setup.

$2\pi a/\lambda_{n,l}$, where $\lambda_{n,l}$ is the light wavelength in vacuum, and a is the radius of the μ -sphere. These MDRs have been verified experimentally at optical wavelengths with micrometer-sized spheres.

Many applications of the microspheres require coupling of light into MDRs from external light sources. The greatest impediment to the use of μ -sphere resonators in practical devices has been the difficulty of efficiently light coupling into and out of the μ -spheres. One way to excite MDRs is to use evanescent coupling method. To couple light into or out of the μ -sphere, 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 fibers, OFHCs, angle-polished fibers, high-index prisms, and planar waveguide couplers.¹⁴ Fiber half couplers are also used to produce polarization splitters, pump/signal combiners, and loss compensators for optical fiber communications. If a μ -sphere is placed on the exposed surface near the evanescent field of the fiber optic core, then there is an efficient energy exchange between the waveguide mode of the fiber and the MDR of the μ -sphere.¹⁵

3 Experimental Setup

A schematic of the experimental setup is shown in Fig. 1. Light is coupled into the microsphere by using an OFHC. 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.¹⁶ The cladding of the fiber below the μ -sphere is shaved down to $0.7\ \mu\text{m}$ 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 μ -sphere. The transmission loss from the OFHC corresponds to 21 dB (0.8%). BK7 glass microspheres are used in the experiment, because glass exhibits low loss at optical communication wavelengths. The glass microsphere has a radius of $a = 500\ \mu\text{m}$ and refractive index of 1.50. Excitation of MDRs of the microsphere is achieved by using a tunable distributed-feedback (DFB) semiconductor laser, whose center wavelength is 810 nm. Wavelength tuning is achieved by tuning the temperature of the DFB laser with a laser diode controller (LDC). Both the

Fig. 2 Temperature tuning spectra of the power transmission (upper curve) and the elastic scattering (lower curve) when the polarizer is at (a) 90 and (b) 0 deg, respectively.

transmitted light through the optical fiber, and the scattered light from the μ -sphere at a right angle (90 deg) are detected. A polarizer is inserted between the microscope and photomultiplier tube (PMT) to separate the TE and the TM MDRs. The PMT signal is sent to a digital oscilloscope for signal 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/wavehead (PWH). Device control and data acquisition are performed with standard IEEE-488 general purpose interface bus (GPIB) interface.

4 Experimental Results

Figure 2 shows the elastic scattering and the power transmission spectra obtained by temperature tuning of the DFB laser between 19 and 32°C at a constant current of 31.2 mA. This temperature ranges corresponds to a wavelength range of 811.9 to 812.7 nm. The spectral resolution of the acquisition system is determined to be 0.04 nm. Figure 2(a) shows the elastic scattering spectrum of the TE MDRs, obtained through a polarizer with its polarization axis at 90 deg to the incoming beam. Figure 2(b) is obtained when the polarizer is placed at 0 deg to the incoming beam, corresponding to TM MDRs. We can clearly observe MDR peaks in the elastic scattering, and the associated dips in the power transmission spectra. In the spectra of Fig. 2, the linewidth (FWHM) of the MDRs of higher intensity is approximately 13 GHz (i.e., 0.03 nm), and the $\Delta\lambda$ of the

higher intensity MDRs is measured to be 63 GHz (0.14 nm), which is consistent with the calculation based on the Mie scattering theory given by

$$\Delta\lambda = [\lambda^2 \arctan(m^2 - 1)^{1/2}] / [2\pi a(m^2 - 1)^{1/2}], \quad (1)$$

where $\Delta\lambda$ is defined as the separation between the adjacent peak wavelengths of the same mode order (l) MDR's with subsequent mode numbers¹⁷ (n). Note that the fractional depth of the dips in the transmission spectra is not the same for all MDRs. This is due to different Q -factors and coupling efficiencies of the MDRs. However, the relative depth of the transmission dips is maintained at each $\Delta\lambda$. The broad Gaussian line shape of the power transmission spectra results from the coupling geometry of the DFB laser to the optical fiber. As the temperature of the DFB laser changes, the input laser spot moves with respect to the fiber core, when entering the OFHC.

5 Coupling Efficiency

Power coupled into the MDRs can be estimated from the power transmission spectra. For example, in the TM spectrum of Fig. 2(b), the MDR at 812.4 nm has a transmitted power of 40 μ W. When the μ -sphere is not present, the transmitted power is estimated to be 43 μ W. Therefore, power coupled (P_i) into the MDR is approximately 3 μ W, which means a 6.9% (i.e., 0.31 dB) coupling loss. The scattered intensity I_i can be expressed¹⁸ as $I_i = P_i / \sigma$, where σ is the scattering cross section of the MDR. For a Gaussian beam, the scattering cross section is defined to be $\sigma = \omega_0 \lambda / \sqrt{2}$, where ω_0 is beam waist's half width.¹⁹ For our experimental parameters of $\omega_0 = 2 \mu$ m and $\lambda = 812.4$ nm, I_i is calculated to be 0.75 kW/cm². We can also calculate the coupling efficiency of a Gaussian beam (σ) into MDRs using the localization principle, where $\langle \sigma \rangle = \sqrt{2} / \pi^2 \omega_0$ is estimated to be 0.053 (i.e., 5.3%), which compares favorably with the observed 6.9% coupling loss.

The measured quality (Q) factor of the MDRs in the scattering spectrum is approximately of 10^4 . The high Q factor MDRs are superimposed on a background of low- Q -factor MDRs. In practice, absorption, scattering on defects, scattering on impurities, and residual surface roughness¹⁸ 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, Q_s^{-1} is the losses due to light scattering by surface roughness and Rayleigh scattering inside the sphere, and Q_{abs}^{-1} is the optical absorption loss. The presence of surface roughness and the molecular roughness would give higher- Q MDRs (Ref. 20), when the beam is aimed slightly inside the sphere's rim.²¹

6 Theoretical Results

For telecom applications of high channel counts, linewidths of the order of several gigahertz and channel spacing of several terahertz are necessary. Microspheres and MDRs can be tailored to enable required channel spacing and linewidths. Factors influencing the MDRs are mainly size and the refractive index of microspheres. To implement these

Fig. 3 Calculated (a) TE and (b) TM mode numbers (n) and mode orders (l) of the BK7 glass microsphere ($a = 50 \mu\text{m}$, $n = 1.50$) between 1530 and 1565 nm.

criteria, we have also theoretically analyzed the MDR spectra of small solid microspheres in the C-band. Generalized Lorenz-Mie theory (GLMT), which is a direct extension of the plane-wave Lorenz-Mie theory, describes electromagnetic elastic scattering of an arbitrary light beam by a spherical particle.²² 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 μ m) propagating just at the edge of the microsphere is used²³ at a scattering angle of 90 deg.

In Figs. 3(a) and 3(b), the mode and order numbers are calculated for both TM and TE MDRs at a wavelength range between 1530 and 1565 nm, corresponding to C-band for a BK7 glass microsphere with the radius of $a = 50 \mu\text{m}$ and a refractive index of $m = 1.50$, respectively. TE and TM elastic scattering spectra for glass microspheres with a radius of 50 μm are calculated in Figs. 4(a) and 4(b). TE and TM elastic scattering spectra show observable MDRs. We also identified the mode numbers and mode orders of the MDRs. Most of the MDRs are not observable in the spectrum due to their high Q -factors. The $\Delta\lambda$ of subsequent mode orders is calculated to be 5.61 nm. The Q -factors of the broadest MDRs are approximately 10^4 .

7 Conclusions

We demonstrated the excitation of MDRs of glass microspheres using an OFHC and a temperature-tunable DFB

Fig. 4 Calculated elastic scattering spectra of the BK7 glass microsphere ($a = 50 \mu\text{m}$, $n = 1.50$) for (a) TE and (b) TM polarization.

laser. MDR peaks in the elastic scattering spectra and associated dips in the transmission spectra were observed experimentally. With the proper system design, it would be possible to totally drop the selected MDR powers from the transmission spectrum. The estimation of coupling efficiencies compares favorably with the experimentally measured values. Simulation results of elastic scattering spectra of glass microspheres in the C-band for data transmission were presented. In conclusion, MDRs of microspheres can be exploited to develop passive multiplexing/demultiplexing modules, optical add/drop multiplexers for WDM communications.

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