Silicon Photonics with Microspheres

Ali Serpengüzel∗, Onur Akatlar, and Adnan Kurt
Koç University, Microphotonics Research Laboratory, Physics Department,
Rumeli Feneri Yolu, Sariyer, Istanbul 34450 Turkey

ABSTRACT

Silicon microspheres coupled to optical fibers have been used for optical channel dropping in the near-IR. The observed morphology dependent resonances had quality factors of 100000. These optical resonances provide the necessary narrow linewidths, that are needed for high resolution optical filtering applications in the near-IR. In addition to filtering, detection, and switching applications of this photonic system is studied in the near-IR as well as far-IR. The silicon microsphere shows promise as a building block for silicon photonics in the near-IR as well as, mid-IR, and far-IR.

Keywords: Channel dropping filter, microsphere, resonator, photonic atom, morphology-dependent resonance, whispering gallery mode, wavelength division multiplexing.

1. INTRODUCTION

Dielectric microspheres have found various photonic applications in the ultraviolet (UV), visible and near-infrared (IR) communication bands [1]. Morphology dependent resonances (MDR’s), i.e., whispering gallery modes (WGM’s), or simply optical resonances of dielectric microspheres provide the necessary optical feedback for applications in spectroscopy, laser science, and optical communications. Among these applications, we can find novel microlasers, optical couplers, and optical filters. Low threshold lasing from rare earth doped silica microspheres [2], polymer microsphere lasers [3] and Raman lasers have been demonstrated. Strain tunable microsphere oscillators [4], add-drop filters [5], and thermo-optical switching [6] 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 any communication network. 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, microspheres can be used as compact channel dropping filters. Recently, we have observed elastic light scattering in silicon microspheres in the near-IR [8]. In this paper, we are investigating the mid-IR communication applications of silicon microspheres.
2. MORPHOLOGY DEPENDENT RESONANCES

A physical interpretation of MDR’s is based on propagation of rays around the inside surface of the microsphere, confined by an almost total internal reflection (TIR) [9]. The rays approach the internal surface at an angle beyond the critical angle and are totally internally reflected each time. After propagating around the microsphere, the rays return to their respective entrance points exactly in phase and then follow the same path all over again without being attenuated by destructive interference [10]. A MDR is specified by a mode order \( l \) (the number of radial intensity maxima) and mode number \( n \) (the number of maxima between 0° and 180° degrees in the angular distribution of the energy of the mode). MDR’s satisfy resonance conditions for specific values of the size parameter \( x = \frac{2\pi a}{\lambda} \), where \( a \) is radius of the sphere and \( \lambda \) is the vacuum wavelength of light [11].

The MDR’s of a microsphere are analyzed by the localization principle [12] and the generalized Lorenz-Mie theory (GLMT) [13]. Each MDR is characterized by a mode number \( n \) and a mode order \( l \). The angular mode number \( n \) gives the number of maxima between 0° and 180° in the polar 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. Each MDR of the microsphere also has an azimuthal angular dependence from 0° to 360°, which is labeled with an azimuthal mode number. However, for spheres, MDR’s differing only in azimuthal mode number have identical resonance frequencies.

The greatest impediment to the use of microsphere resonators in practical devices has been the difficulty of efficiently coupling light into and out of the microspheres. Light can be coupled into the microsphere using different types of coupling devices: side-polished optical fibers [14], prisms [15] and tapered optical fibers [16]. The principle of these devices is based on providing efficient energy transfer to the resonant circular TIR guided wave in the microsphere resonator (representing the MDR mode) through the evanescent field. Efficient coupling can be expected if two main conditions are satisfied: phase synchronism and significant overlap of the two waves modeling the MDR mode and the coupler mode. The coupling is based on the fact that the modal field of the guided mode extends beyond the core-cladding interface.

3. SILICON MICROSPHERES

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 [17]. Additionally, the need for low cost photonic devices has stimulated a significant amount of research in silicon photonics [18]. 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 [19].

Silicon microspheres with their MDR’s are a new paradigm for the use of silicon in optical communication applications. The MDR peaks in the elastic scattering spectrum and associated dips in the transmission spectrum are experimentally observed by coupling the light from an optical fiber half coupler (OFHC) to the MDR’s of a silicon microsphere placed on the OFHC surface. Silicon microspheres with their high Q MDR’s of \( 10^5 \) can be used as active channel-dropping filters. The Q-factor of a MDR, \( Q = \frac{\lambda}{\delta \lambda} \), gives information about the lifetime and linewidth of the resonance [20].
4. ELASTIC SCATTERING CALCULATIONS

We have investigated the feasibility of THz communication filters using silicon microspheres. Elastic light scattering from a silicon microsphere with radius $a = 50 \, \mu m$, and a refractive index $m = 3.4224 + 0.00003i$ [21] is calculated. Forward ($0^\circ$), perpendicular ($90^\circ$), and backward ($180^\circ$) normalized elastic scattering intensities are simulated at wavelengths between 9.8 $\mu m$ to 10.6 $\mu m$.

Figure 1 shows the accepted TE, TM polarization directions that are used in calculations. A plane wave is incident on a silicon microsphere of radius 50 $\mu m$ and a refractive index $m = 3.4224 + 0.00003i$. TE polarization represents the plane wave with parallel polarization. TM polarization represents the plane wave with perpendicular ($\perp$) polarization. Note that TE and TM components give the same results for $0^\circ$ and $180^\circ$ scatterings. But the $90^\circ$ scattering depends on the TE and TM polarizations. At $90^\circ$ scattering only the even mode number ($n$) resonances can be observed. The mode spacing between the adjacent MDR’s of same ($n$) mode number and consecutive mode order ($l$) is calculated to be $0.124 \, \mu m$ at $\lambda = 10 \, \mu m$ using $\Delta\lambda = \lambda^2 \arctan(m^2-1)^{1/2} / 2\pi a(m^2-1)^{1/2}$.

Figure 2 illustrates the results of the simulation for backward ($180^\circ$) scattering from a microsphere of radius $a = 50 \, \mu m$ and refractive index of $m = 3.4224+0.00003i$. The highest $Q$ factor of both the TE and the TM MDR’s are on the order of $10^5$. The mode spacing between adjacent MDR’s is 0.121 $\mu m$, which correlates well with the calculated value of 0.124 $\mu m$. 

![Geometry of the elastic scattering calculations.](image1)

![180° normalized scattering intensity from a silicon microsphere.](image2)
Figure 3 illustrates the forward (0°) scattering from the microsphere. The highest Q factor of both the TE and the TM MDR’s are on the order of $10^5$. The calculated separation between adjacent MDR’s at 10 µm is 0.124 µm, which correlates well with the value obtained from the figure (0.129 µm).

Figure 4 and 5 show the normalized elastic scattering intensity from a silicon microsphere at 90°. The highest Q factor of both the TE and the TM MDR’s are on the order of $10^5$. The spacing between the adjacent MDR peaks is 0.246 µm and 0.312 µm for TE and TM polarizations, respectively. Only even mode number (n) resonances can be detected at 90° scattering, [22] therefore mode spacing between adjacent mode numbers (n) and consecutive mode orders (l) is observed to be twice of the calculated value of 0.124 µm.
5. CONCLUSIONS

We have calculated the elastic scattering spectra of silicon microspheres in the THz band. The mode spacing $\Delta \lambda$, i.e. wavelength difference between consecutive mode numbers (n) with the same mode order (l), is estimated and calculated to be 0.124 $\mu$m. The 90° elastic scattering occurs only for even mode number MDR’s, as a consequence, the mode spacing is two times bigger than any other angle. The linewidths $\delta \lambda$ of the highest mode order MDR’s are measured to be 0.001 $\mu$m, which results in a quality factor ($Q = \lambda / \delta \lambda$) of approximately $10^5$. With the proper system design, it would be possible to use silicon microspheres for space and earth based communication applications. The silicon microsphere shows promise as a building block for future microoptoelectronic integration.

6. ACKNOWLEDGMENTS

We would like to acknowledge the partial support of this research by the European Commission Grant No: FP6-IST-511616: PHOREMOST and FP6-IST-003887 NEMO.

7. REFERENCES