Silicon-Nanocrystal-Coated Silica Microsphere Thermo-optical Switch

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Abstract—We report on a low-switching-energy, all-optical fiber switch that consists of a silica microsphere resonator coated with a silica layer containing silicon nanocrystals. A signal at 1450 nm and a pump at 488 nm are coupled into the microsphere through a tapered fiber. When a pump pulse is launched into the sphere, it is absorbed by the nanocrystal layer, causing the sphere to heat up and change its refractive index. The index change can be exploited to switch the signal by shifting the microsphere resonance. A resonance wavelength shift of 5 pm, sufficient to fully switch the signal, was observed with a pump pulse energy of only 85 nJ. The rise time of the switch was ∼25 ms (limited by the pump peak power) and its fall time was ∼30 ms (limited by the sphere’s thermal time constant). The product of the switching peak power (3.4 µW) and the device’s characteristic dimension (a diameter of 150 μm) is 5.1 × 10^−10 Wm, one of the lowest values reported for an all-optical fiber switch.

Index Terms—Microsphere, optical resonator, optical switch, silicon nanocrystals.

I. INTRODUCTION

All-optical fiber switches are important devices that have been researched for many years mainly because of the critical need for low-loss, low-power, fiber-interfaced, optically addressable switching devices in optical communication and fiber sensor systems. These include periodic self-healing communication networks, reconfigurable optical signal processing, packet switching for local area networks, bit switching, towed sensor arrays, and testing of fiber links. Unfortunately, very few physical mechanisms are available to modulate the refractive index of a silica fiber in order to induce switching. The widely studied Kerr effect has an extremely fast response time (a few femtoseconds) but it is notoriously weak: Kerr-based fiber switches require of the order of 20 W in a 10-m fiber at 1.55 μm signal. The use of the resonator greatly reduces the switching power: a pump exposure of only 4.9 mW for ∼0.5 s was sufficient to shift the resonance by ∼1000 linewidths. Since full switching requires a shift of about one linewidth, the switching power was only 4.9 μW and the switching energy ∼2.5 μJ. The switch response time was, however, very long (0.165 s). Taking the characteristic dimension of such a switch to be the sphere diameter (250 μm in this case), this device has a PL product of ∼1.2 × 10^−9 Wm, which is very low. Compared to the other all-optical fiber switches, this new class offers the unique advantages of an extremely small size (a microsphere is typically only 50–500 μm in diameter) and a very low switching energy. This is because the resonator has such sharp resonances that a very small change in the microsphere index is sufficient to induce full switching.

II. METHOD

In this paper, we demonstrate a microsphere switch based on the same concept that was used by Tapalian et al. [6] and improves on this result in several ways. It consists of a high-Q silica microsphere coated with a thin layer of silicon-rich silicon oxide (SRSO) in which nanocrystals of silicon are precipitated. The advantage of using the Si nanocrystals as an absorber instead of a polymer are: 1) it is compatible with the standard micro-fabrication technologies and 2) Si nanocrystals have a broad absorption band that extends into the near IR, thus this device can advantageously be pumped with a standard laser diode, e.g., at 808 nm. Also, this device uses a standard multiplexing scheme to couple the pump and the signal into the microsphere through the same bi-tapered fiber, which yields a more efficient utilization of the pump energy. With a 488-nm pump, we demonstrate full switching with only ∼3.4 μW of the pump peak power (switching energy of ∼85 nJ), which is in good agreement with the prediction of a simple thermal model. The switch fall time is measured to be ∼30 ms, which is approximately five times faster than the one previously reported in [6], and is in agreement with the predictions given in [7].

The microspheres were fabricated by melting the tip of a single-mode fiber (Corning SMF-28E) with a 125-W 10.6-μm...
CO₂ laser. The typical Q-factor of our microspheres around 1450 nm was measured to be \( \sim 5 \times 10^7 \). The microspheres were coated at the Korea Institute of Science and Technology (KAIST) with a 140-nm layer of SRSO using inductively coupled plasma-enhanced chemical vapor deposition [8], while rotating the spheres to ensure an even coating. They were then annealed at 1100°C for 60 min to precipitate the silicon nanocrystals. The presence of the nanocrystals was confirmed in the selected samples with the transmission electron microscopy (not shown). The reference samples were coated with silica instead of SRSO. As expected, no nanocrystals were detected in these samples. Since the signal (\( \sim 1450 \text{ nm} \)) falls out of the absorption band of the Si nanocrystals, it is negligibly absorbed by the coating, and the coated microspheres have a high \( Q \), of the order of \( 3 \times 10^5 \).

A diagram of the experimental switch is shown in Fig. 1. The signal was provided by a narrow-band tunable source of frequency around 1450 nm. The pump was a 488-nm Ar-ion laser modulated into the pulses of adjustable width with a mechanical chopper. The signal and the pump were multiplexed through a commercial wavelength division multiplexing (WDM) fiber coupler, and the multiplexer output was coupled into the microsphere through a bi-tapered single-mode fiber with a neck diameter of a few micrometers. Although the signal is critically coupled and guided around the sphere in a whispering gallery mode, the pump is not of a single frequency and is significantly absorbed by the SRSO coating, so that it resonates poorly, if at all. In the absence of the pump, the signal is depleted, mostly by scattering, as it resonates around the sphere and no signal comes out of the tapered fiber’s output port. When a pump pulse is launched into the microsphere, its energy is absorbed by the nanocrystals, which are excited above their bandgap. As they relax to the ground state, heat is generated and transferred to the silica host. The resulting increase in the temperature changes the sphere’s refractive index and causes its resonance wavelengths to shift. When the shift is large enough, the (fixed) signal no longer falls on a resonance, and the signal power comes out of the output port, implying that the signal has been switched. After the pump pulse has passed through, the microsphere cools down to its initial temperature through the convection into the surrounding air, its resonance wavelengths return to their initial values, the signal becomes resonant again, and no signal power comes out of the tapered fiber. The role of the nanocrystals is to increase the pump absorption compared to the pump scattering loss, which increases the fraction of the pump energy turned into heat, and thus, reduces the pump energy required for the switching.

The switching energy of our device can be evaluated with a simple thermal model. When the microsphere is heated, its refractive index changes through the index thermal coefficient \( \partial n/\partial T \) of silica, and its diameter changes through the thermal expansion of silica. Since the effect of the thermal expansion on the resonance wavelength is about two orders of magnitude weaker than that of the index change, it can conveniently be neglected. For our experimental conditions, it was also verified that the free carriers generated in the nanocrystals by the pump beam had a negligible effect on the signal absorption and the sphere index. The switching energy can, therefore, be obtained by first calculating the index change required to shift the signal resonance by one linewidth (which is sufficient to fully switch the signal), and then, calculating the heat it takes to change the microsphere index by this amount. The change with temperature in the resonance wavelengths of a microsphere of around 1450 nm, calculated from the sphere’s resonant condition and the \( \partial n/\partial T \) of silica (\( \sim 10^{-5} ^\circ \text{C}^{-1} \)), is \( \sim 10 \text{ pm} / ^\circ \text{C} \). For small temperature increases (\( \delta T < 1 ^\circ \text{C} \) for this switch), by analogy with an optical fiber [9], the temperature of the microsphere in steady state (i.e., after the pump has been on for a time longer than the sphere’s relaxation time) is close to uniform. According to energy conservation requirement the heat that must be injected into the sphere per unit time to maintain its steady-state temperature at a temperature \( \delta T \) above the temperature of the surrounding air is given by [9]

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\dot{H} = h A \delta T
\]  

where \( h \) is the heat transfer coefficient of the silica in air due to the natural convection, and \( A \) is the sphere area. If \( P_{\text{abs}} \) is the pump power absorbed by the microsphere, steady-state switching is achieved for \( P_{\text{abs}} = \dot{H} \). For our sphere (150-\( \mu \text{m} \) diameter, \( Q \approx 3 \times 10^5 \)), the resonance linewidth is around 1450 nm, and thus, the wavelength shift required for the full switching is \( \sim 4.8 \text{ pm} \). This requires a temperature change of \( \delta T \approx 4.8/10 = 0.48 ^\circ \text{C} \). Taking the \( h \) coefficient of a silica sphere to be the same as for a silica cylinder (\( h = 81 \text{ W/m}^2/^\circ \text{C} \)) [9], we estimate from (1) that the absorbed pump power required for switching is \( \sim 2.9 \mu \text{W} \).

The degree of switching was monitored experimentally by continuously scanning the signal wavelength over the resonance to record the resonance dip on a digitizing oscilloscope. This measurement was then repeated with the pump laser on to record the shift in resonance after the steady state was reached.

The taper was fairly lossy at the pump wavelength (approximately 12 mW of power was coupled into the fiber but only 0.03% was transmitted). Hence, the taper loss at the pump wavelength had to be measured in order to determine the pump power coupled into the microsphere. This was done by measuring the pump power coupled into and exiting the tapered fiber when the sphere was coupled to the tapered fiber, and when it was decoupled from the fiber. This measurement was repeated after reversing the ports of the tapered fiber, i.e., when coupling the pump at
the output port. It can be shown easily that this set of measurements unambiguously yields the transmission loss of the two tapered fiber sections (input to neck and neck to output) and the pump power absorbed in the sphere. Knight et al. have shown that the adiabatic tapers with very small (<0.1 dB) tapering losses can be obtained experimentally [10], allowing for a more direct determination of the pump power coupled into the sphere.

To illustrate switching, we show the transmission spectrum of the microsphere, measured with and without the pump in Fig. 2. The resonance has a full-width at half-maximum (FWHM) of 4.8 pm ($Q \approx 3 \times 10^5$). The shift in the resonance wavelength in the figure is 5 pm for a pump power of 3.4 $\mu$W. This shift was observed to further increase with increasing pump power. This switching power agrees well with the value of 2.9 $\mu$W, predicted theoretically earlier. From this measured value and the diameter of our microsphere (150 $\mu$m), the calculated PL product of our switch is $5.1 \times 10^{-10}$ Wm, or a factor of 3 lower than that reported by others [6]. In the reference samples, whose coating did not contain the Si nanocrystals, the shift induced by the pump was smaller by a factor of $\sim 3.3$. This confirms that the nanocrystals increase the pump absorption, and thus, significantly reduce the switching energy requirement, compared to the uncoated microspheres with the same $Q$. It is also worth pointing out that the $Q$-factor (related to the resonance linewidth) does not change upon switching. This implies that the increase in the absorption due to the free carrier generation by the pump does not have a significant effect on $Q$, as stated earlier.

Fig. 3 shows the temporal response of the switch. This curve was measured by tuning the signal to a resonance and adjusting the spacing between the tapered fiber and the sphere to realize critical coupling (zero transmitted signal power). The pump pulses were then turned on (150-ms width, 50% duty cycle, sub-ms rise and fall time) and the signal power transmitted by the tapered fiber was recorded as a function of time. The falling and rising edges of the switched pulse are approximately exponential, as expected. Fitting an exponential to the two edges gave a rise time constant of $25 \pm 5$ ms and a fall time constant of $30 \pm 5$ ms. The latter agrees well with the value calculated from [7] for our microsphere’s dimension. Note that it is dictated by the time required for the sphere temperature to reach the equilibrium with the surrounding air after the pump pulse has been turned off. If we were to use microtoroids instead of the microspheres, the fall time could be faster [11], as the microtoroids have a smaller thermal mass. The rise time is imposed by the rate at which heat is deposited into the sphere, i.e., by the pump power. It is purely coincidental that the measured rise and fall time constants are comparable. From the rise time, the total energy required for the full switching is estimated to be $3.4 \mu$W $\times$ 25 ms $\approx$ 85 nJ. This is lower than the previously reported value by a factor of $\sim 30$ [6].

III. CONCLUSION

In summary, we have demonstrated a novel all-optical switch using a silica microsphere resonator coated with silicon nanocrystals. The pump and the signal wavelengths are multiplexed and coupled into the microsphere through a tapered fiber. A resonance wavelength shift of 5 pm, sufficient to induce the full switching of a signal at 1450 nm, was observed with a pump pulse energy of only 85 nJ. The rise and fall time constants of the switch were measured to be $\sim 25$ and $\sim 30$ ms, respectively. The product of the peak power required for the switching (3.4 $\mu$W) by the device length (150 $\mu$m) is $5.1 \times 10^{-10}$ Wm, which is one of the lowest values reported for an all-optical fiber switch.

REFERENCES


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