

Dynamical electrical tuning of a silicon microsphere: used for spectral mapping of the optical resonances

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In this work, electrical square pulses at various duty cycles are applied to a silicon microsphere resonator in order to continuously tune the refractive index of a silicon microsphere and to map the optical resonance in the time domain. A continuous-wave semiconductor diode laser operating in the L-band is used for the excitation of the silicon microsphere optical resonances. The 90° transverse magnetically polarized elastic scattering signal is used to monitor the silicon microsphere resonances. We show that at a constant input laser wavelength, up to five high-quality-factor optical resonances can be scanned by dynamical electrical tuning of the silicon microsphere cavity. © 2014 Optical Society of America

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1. Introduction

Silicon photonics [1] is currently facilitating the merger of electronics and photonics [2] using microresonators as the key elements for optical information processing [3]. Additionally, these silicon microring resonators integrated to microfluidics are opening up complementary application areas such as optical sensing and cavity-enhanced spectroscopy [4,5]. Silicon microspheres providing confinement of light in all three dimensions are realized as 3D microcavities and are shown to exhibit high-quality-factor (*Q*-factor) resonances [6–8].

Dynamic control of light signals can be achieved by perturbing the refractive index of silicon microresonators, which is widely applied in silicon photonics [9]. The refractive index of silicon can be altered

by all-optical [10], thermo-optical [11], and electro-optical means [12]. Electro-optic effects, such as Franz–Keldysh and Kerr effects, are extremely weak for silicon. Moreover, the inversion symmetry of silicon precludes the linear electro-optic (Pockels) effect [13]. The most effective way that electro-optical modulation in silicon can be achieved is by means of the plasma dispersion effect [14] or the thermo-optical effect [15].

Recently, we have shown that the morphology-dependent resonances (MDRs) [16] of a silicon microsphere can be shifted in wavelength [17] and modulated in time [18] with electrical input signals. Spectral mapping of these MDRs is usually performed by scanning the input laser wavelength. Here, we report for the first time to our knowledge, the dynamical electrical tuning of a silicon microsphere at a constant input laser wavelength to map the high-*Q*-factor optical resonances of the silicon microsphere in time.

2. Experimental Setup

The schematic of the experimental setup is shown in Fig. 1. A continuous-wave diode laser is used to excite the MDRs of the silicon microsphere with a radius of 500 μm and refractive index $m = 3.48$. The laser is operated at $\lambda_{\text{laser}} = 1546.7 \text{ nm}$ (in the L-band) and has a linewidth of $\delta\lambda = 0.02 \text{ nm}$, which sets an upper limit on the observable Q -factor of the order of 10^5 . The diode laser temperature is fixed to 25.53°C with a laser diode controller. The operating electrical current of the laser is set to 235.5 mA, which corresponds to an operating optical power of 25 mW. All optical fibers used in the experiment are single-mode. An optical fiber polarization controller is placed at the output of the diode laser to control the polarization of the light propagating in the optical fiber. A red fault locator is used through a Y-coupler to illuminate the evanescent coupling spot on the optical fiber half-coupler (OFHC). The silicon microsphere is positioned on top of the red fault locator spot, marking the evanescent coupling region. The red fault locator is later turned off during the measurements. The optical power of the excitation laser is detected by an InGaAs power wave head and monitored with an optical multimeter. The input laser wavelength is measured via the multimeter and is fixed to 1546.7 nm during measurements. The 90° elastically scattered signal from the silicon microsphere is collected by a microscope lens through a Glan polarizer and is detected by an InGaAs photodiode. The Glan polarizer is used to discriminate between the transverse electric and transverse magnetic (TM) polarized MDRs of the silicon microsphere. The light transmitted through the OFHC is detected by another InGaAs photodiode connected to a lock-in amplifier. The signal transmitted from the lock-in amplifier, the 90° elastic scattering signal, and the electrical input signal are all fed to a digital storage oscilloscope for signal monitoring and data acquisition. An electronic signal generator is used to apply square pulses to the silicon microsphere.

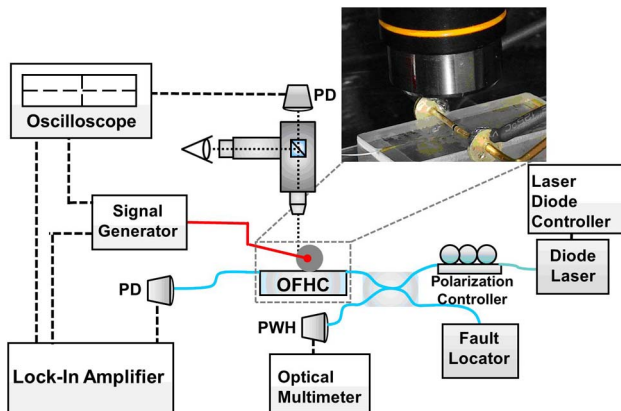


Fig. 1. Schematic of the experimental setup, illustrating the input diode laser, the OFHC, and the silicon microsphere modulated by the signal generator. The 90° TM elastic scattering signal is measured during the tuning of the silicon microsphere. The microsphere is placed on top of the OFHC. The gold probes hold the sphere and at the same time are used as electrical probes.

The electrical signal is applied to the silicon microsphere using golden probes as shown in the inset in Fig. 1.

3. Transient Response of the Silicon Microsphere

In order to map the transient optoelectronic response of the silicon microsphere, an electrical signal of 10 V at a repetition rate of 10 Hz and at various duty cycles is applied to the silicon microsphere. Figure 2 shows the TM polarized 90° elastic scattering signal for the input electrical square pulse operating at duty cycles from 3% to 58%. The on-time of the applied electrical signal is illustrated in Fig. 2 by the shaded regions. The relative setting of the input laser wavelength (λ_{laser}) with respect to the MDRs, before the applied electrical signal, determines whether the elastic scattering signal will decrease or increase with the applied electrical signal as can be seen in Figs. 2(a)–2(h). In Fig. 2, we also see that the initial elastic scattering intensities differ when no electrical signal is applied to the silicon microsphere; possibly since the silicon microsphere might also be heating up and the refractive index not recovering fully during the off-time [19]. The amplitude and duty cycle of the applied electrical signal together determine the amount of spectral shift of the MDRs. As a result, when the duty cycle of the applied electrical signal is increased, local maxima and minima are observed in the elastic scattering signal, as shown in Fig. 2.

In summary, the TM polarized 90° elastic scattering signal repeats itself in every period of the applied electrical signal. During the on-time, there is a variation, which reverses itself during the off-time as shown in Fig. 2. This transient optoelectronic response of the silicon microsphere can be understood by an electrical current-dependent spectral shift during the on-time and an equal and opposite spectral shift during the off-time of the applied electrical signal. As the duty cycle of the applied electrical signal increases, the elastic scattering signal detected

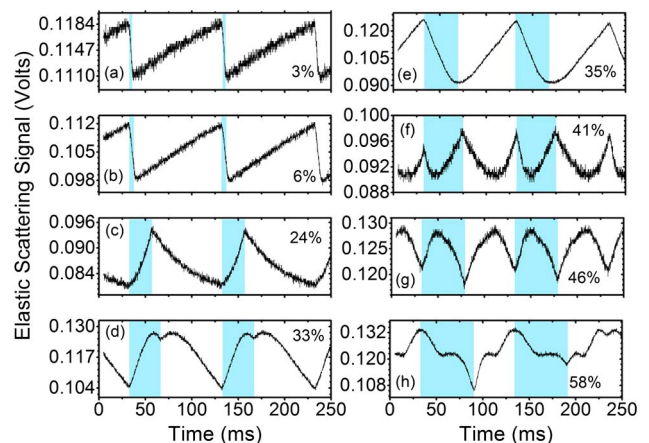


Fig. 2. TM polarized 90° elastic scattering signal at (a) 3%, (b) 6%, (c) 24%, (d) 33%, (e) 35%, (f) 41%, (g) 46%, and (h) 58% duty cycles. The shaded regions indicate the timing and duration of the applied electrical signal.

(observed in a time window Δt) maps a larger spectral span ($\Delta\lambda$), corresponding to a larger section of the MDR spectrum being scanned dynamically at a constant wavelength.

Figure 3 depicts a schematic representation of tuning the silicon microsphere MDRs over λ_{laser} . The dashed curve shows an MDR when there is no electrical signal applied to the silicon microsphere. The solid curve shows the spectrally shifted MDR when an electrical signal is applied to the silicon microsphere. During the application of the electrical signal, the elastic scattering signal changes from an initial (i) to a final (f) value, which is represented by the solid curve. The detected elastic scattering signal that we show in Fig. 2 follows similar spectral curves for different values of the duty cycle, which determines the spectral shift.

4. Dynamical Electrical Tuning of the Silicon Microsphere

We apply an electrical signal to the silicon microsphere for a longer duration and at a slower rate to tune the resonances for a larger span and to map the resonances in time. In order to map the MDRs of the silicon microsphere, we apply a 10 V electrical signal to the silicon microsphere at a repetition rate of 0.1 Hz and at 30% duty cycle. We measure the TM polarized 90° elastic scattering signal from the silicon microsphere. Figure 4(a) shows the electrical signal applied at 30% duty cycle and Fig. 4(b) shows the corresponding TM polarized 90° elastic scattering signal. Figures 4(c) and 4(d) show the TM polarized 90° elastic scattering signal for the on-time and off-time of the applied electrical signal, respectively.

During the tuning of the sphere, we dynamically map multiple MDRs. In Fig. 4(c), after the observation of a total of five MDRs (three in the beginning and two afterward), the elastic scattering signal reaches a steady-state value. In Fig. 4(d), the elastic scattering signal spectrum reverses itself, i.e., after the observation of the three MDRs in the beginning, the signal reaches a steady-state value, and the

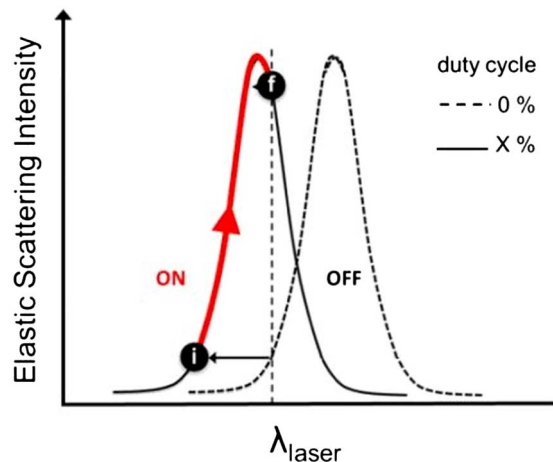


Fig. 3. Representation of dynamically tuning an MDR by applying an electrical signal to the silicon microsphere.

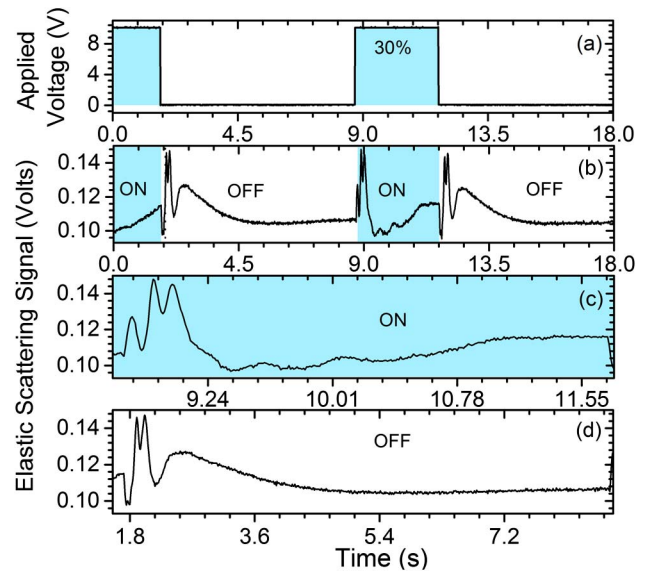


Fig. 4. (a) 30% duty cycle input electrical pulse. TM 90° elastic scattering signal during (b) the total time, (c) on-time, and (d) off-time. The shaded regions indicate the timing and duration of the applied electrical signal.

two later MDRs are buried in the background. The response of the steady-state response of the silicon microsphere can again be understood by an electrical current-dependent spectral shift during the on-time and an equal and opposite spectral shift during the off-time of the applied electrical signal.

The elastic scattering signal in Fig. 4 corresponds to a longer wavelength span ($\Delta\lambda$) given the increased duration of the applied electrical signal. Figure 4 shows that a slowly modulated elastic scattering signal can be used to perform spectroscopy by tuning the refractive index of the silicon resonator, at a fixed narrow-band input laser frequency, in the time domain.

5. Conclusion

In summary, we have demonstrated dynamical electrical tuning of silicon microsphere high- Q -factor ($Q = 10^5$) MDRs in the TM polarized 90° elastic scattering spectrum. The resolution of the MDRs observed is limited by the linewidth of the input diode laser. At short time scales, part of an MDR is scanned by electrically tuning the silicon microsphere at a constant input laser wavelength. At longer time scales, multiple MDRs are observed by electrically tuning the silicon microsphere at a constant single input laser wavelength. This optoelectronic configuration of the silicon microsphere with electronic probes/holders and coupled to a single-mode optical fiber heralds novel applications for spectroscopy without using a tunable or wide-band excitation source.

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