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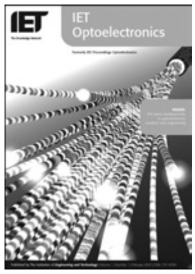

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Electro-optic bistability in a $LiNbO_3$ microdisk resonator

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Abstract: The authors experimentally demonstrate feedback-controlled electro-optic bistability in the whispering gallery travelling-wave optical resonance of a $LiNbO_3$ microdisk. Simulations confirm the physical origin of the behaviour.

1 Introduction

It is well known that a Fabry–Perot (FP) resonator containing an active electro-optic medium can function as a bistable optical device [1]. This behaviour is triggered when the electro-optic element is driven by an electrical signal proportional to the optical output power. Bistable FP resonators have been demonstrated by placing an electro-optic crystal (such as $LiNbO_3$) inside a resonator [1] and also by embedding an FP resonator inside the electro-optic medium using a monolithic waveguide [2]. Similarly, in a $LiNbO_3$ microdisk optical resonator [3], whispering gallery (WG) resonances that exist tightly confined near the disk periphery can be modulated by applying an electric field. Because of the high quality factor (Q) of WG modes ($Q > 10^6$) and the large electro-optic coefficient of $LiNbO_3$ material, this device can have a strong electro-optic response.

Previously, we reported the use of $LiNbO_3$ microdisk in a resonant optical modulator and microwave-photonic receiver [3–5]. Here, we show that the same device can be configured as an electro-optic bistable switch. Experimental results demonstrate that a strong nonlinearity and bistability exists when the applied electric field on the microdisk is proportional to the optical modulator output. As an electrically controlled nonlinear optical device, a resonator-based bistable optical switch may be of importance for switching applications in future optical communication and information processing systems [6].

2 Experimental results

We use a z-cut $LiNbO_3$ disk-shaped optical resonator with curved sidewalls. The $LiNbO_3$ disk has a radius of $R = 2.92$ mm and a thickness of $h = 0.70$ mm (Fig. 1*a*). The z-axis is normal to the disk plane. To support high-Q WG modes, the sidewalls of the disk have a highly polished surface. This is achieved using special polishing techniques that were originally developed in our laboratory and also in a commercial facility [7]. Laser light is evanescently coupled into and out of the resonator via two diamond prisms [3]. Diamond is used because its refractive index of 2.4 is suitably larger than that of $LiNbO_3$ which has a refractive index of 2.14, near $\lambda = 1550$ nm wavelength. The prisms are laser-cut from type I-A natural diamond (from Drukker International B.V., The Netherlands) with entry and exit faces 60° to the base (Fig. 1*b*). The prisms are mounted on spring-loaded aluminium holders that keep them in contact with the microdisk. Fig. 1*b* shows a photograph of the microprisms and the microdisk. Note that evanescent couplers add an external loss to the intrinsic loss of the cavity (caused by surface roughness and absorption). The measured quality factor, Q (also referred to as the loaded quality factor) corresponds to the total loss and is always less than the intrinsic quality factor (Q_0). A copper metal ring electrode on top of the microdisk allows application of a z-directed electric field that overlaps the modal volume of the optical resonance (Fig. 1*c*). A voltage applied to the copper ring electrode controls the electric field between the ring and the substrate (electrical ground). An aspheric lens is used to

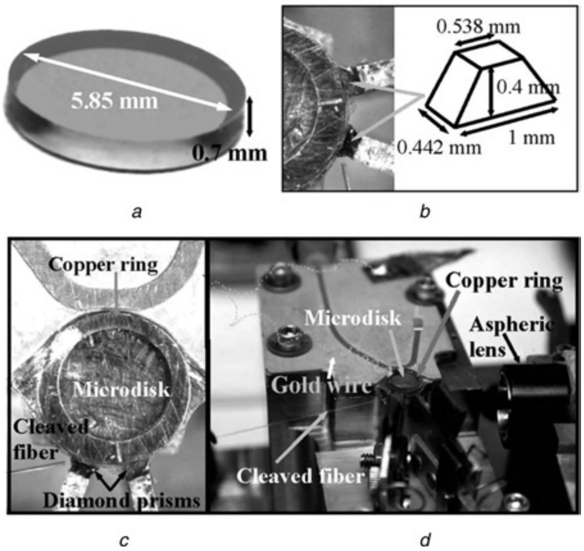

Figure 1 *Photograph of the microprisms and the microdisk*

a Photograph of a $LiNbO_3$ microdisk optical resonator
b Diamond microprisms are used to couple laser light into and out of the microdisk. The right panel is a schematic diagram showing the dimensions of the microprism
c Top-view photograph showing the microprisms, the $LiNbO_3$ microdisk mounted on a radiofrequency-printed circuit board, and the copper metal ring placed on top of the microdisk
d Photograph of the experimental arrangement for optical coupling and electro-optic control

focus and couple the input laser beam to WG modes through the first prism (Fig. 1*d*). A cleaved single-mode fibre in the vicinity of the second prism is used to collect and guide the optical output power to a photodetector (Figs. 1*c* and 1*d*).

A schematic diagram of the experimental arrangement used to measure electro-optic nonlinearity is shown in Fig. 2. To study electro-optic bistability in this configuration, the amplified detector output voltage is fed back to the ring electrode, so that the voltage applied to the electrode is a function of resonator optical output power. We use a polariser to selectively excite TE or TM optical modes inside the disk. In this experiment, TE-polarised modes (optical E-field in the z-direction) are chosen as their resonant wavelength is most strongly affected by the E-field along the z-axis. The response of the selected mode is evaluated by applying a DC voltage on the copper ring and measuring the resonant wavelength shift. As shown in Fig. 3*a*, an applied electric field changes the effective refractive index seen by light and shifts the spectral position of the high-Q TE WG resonances. The measured electro-optic sensitivity in this case is 0.09 pm/V. Optical input power to the resonator is provided by a frequency-stabilised laser diode whose output is intensity modulated to create a 500 Hz triangle wave. Fig. 3*b* shows the temporal behaviour of the detected optical output power in the presence (black line) and in the absence (grey line) of the feedback voltage on the ring electrode. The presence of feedback results in nonlinear behaviour. When optical output power is plotted against optical input power, the resulting bistable behaviour manifests itself as a hysteresis loop. Fig. 4*a* shows the measured optical output power as a function of optical input power for the indicated values of peak-to-peak voltage feedback (V_{fb}) and loaded optical Q-factor. Using an optical mode with $Q = 7.5 \times 10^5$, the electro-optic system shows a slight nonlinearity when $V_{fb} = 1.5$ V. Using an optical

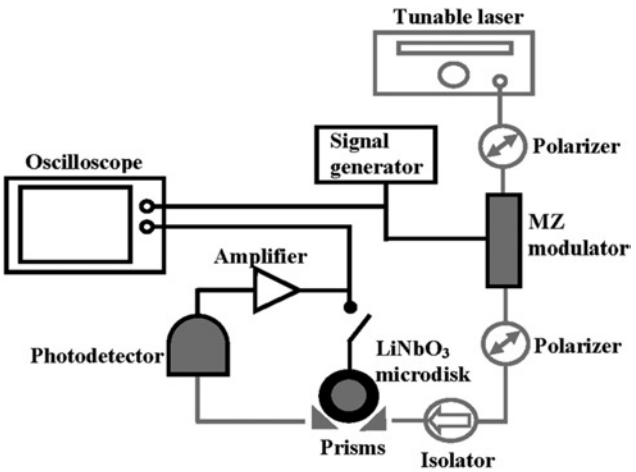

Figure 2 *Experimental arrangement to measure electro-optically induced nonlinearity*

The voltage applied to the electrode is proportional to the resonator optical output power

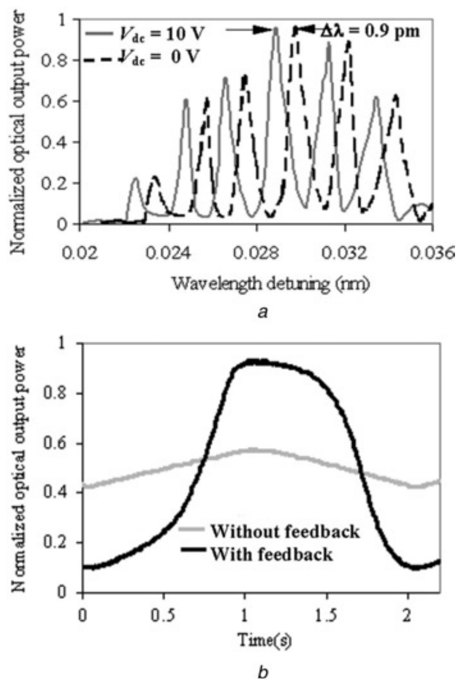

Figure 3 *Applied electric field changes the effective refractive index seen by light and shifts the spectral position of the high-Q TE whispering gallery resonances*

a Measured optical spectrum of the TE WG modes in the presence (solid line) and absence (dashed line) of a DC electric field
b Temporal behaviour of the optical power with and without the feedback voltage on the copper ring

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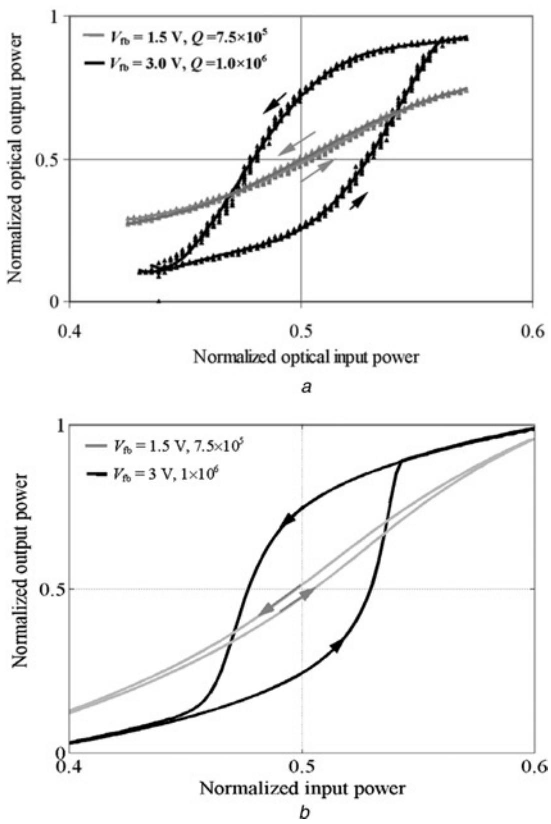

Figure 4 *Experimental results*

a Experimental results demonstrating nonlinear behaviour of optical output power as a function of optical input power for the indicated values of feedback voltage, V_{fb} and optical Q-factors. The solid lines are polynomial fits to the experimental data
b Simulation results for an ideal resonator showing behaviour similar to (*a*)

mode with $Q = 1 \times 10^6$ and $V_{fb} = 3.0$ V, significant bistability and hysteresis behaviour are observed. The arrows indicate the sense of the hysteresis loop. Fig. 4*b* shows the results of simulation for the ideal case where just one set of modes has been excited inside the disk. The simulation shows a behaviour similar to the experimental results of Fig. 4*a*. For this simulation, the transfer function, $H(\omega)$ of a general resonator-coupler system is used, $H(\omega) = -\kappa^2 e^{\delta/2}/(1-(1-\kappa^2)e^{\delta})$. Here, ω is the optical frequency,κ the optical coupling factor and the phase, $\delta = -\alpha + i\phi$, where α is the optical loss per round-trip and ϕ the phase change of the optical electrical field per round-trip. The feedback voltage applied to the disk, V_{fb}, is proportional to the optical output intensity, I_{out} (ω), of the resonator. This voltage creates an electric field along the z-direction of $E_z = V_{fb}/h$, which changes the refractive index at incident optical wavelength $\lambda = 1550$ nm from $n_e(0) = 2.138$ to $n_e = n_e(0) - n_e^3 r_{33} E_z/2$. For this simulation, $\alpha = 0.0001$/m, whereas the coupling factor is set to $\kappa = 0.39$ and $\kappa = 0.325$ for $Q = 7.5 \times 10^5$ and $Q = 1 \times 10^6$, respectively. The electro-optic coefficient of $LiNbO_3$ along the c-axis is $r_{33} = 30.8$ pm/V. The phase δ in the transfer function depends on the refractive index and therefore on the feedback voltage (V_{fb}). Hence, with feedback, the transfer function depends on optical output power as well as optical frequency. The optical output power, $I_{out}(\omega)$, of the system is calculated by applying a discretised triangular input signal and solving the equation $I_{out}(\omega) = H(\omega, I_{out}) \times I_{in}(\omega)$ iteratively. The optical frequency is set to $\omega_0 - \Delta\omega/2$ where ω_0 is a resonant frequency of the disk and $\Delta\omega$ the spectral line width of the optical resonance.

3 Discussion

The strength of the electro-optic nonlinearity in a $LiNbO_3$ microdisk resonator with voltage feedback is proportional to the quality factor of the optical mode as well as the feedback gain. The switching speed is limited by the characteristic response time of the electromagnetic resonance (photon lifetime, τ) and consequently it is inversely proportional to the loaded optical quality factor (Q). This trade-off between sensitivity and speed is an important factor that should be considered in bistable electro-optic switch design. The fabricated device has a Q of about 10^6 that corresponds to a photon lifetime of about 0.8 ns at $\lambda = 1550$ nm ($\tau = Q/\omega$). Therefore the maximum switching frequency for this device is limited to about 0.2 GHz $\sim 1/2\pi\tau$). One way of improving sensitivity without sacrificing speed is increasing the strength of the feedback E-field. This may be achieved by reducing the microdisk thickness as well as increasing the voltage feedback gain.

We note that bistable optical behaviour was previously reported in semiconductor microring resonators [8]. However, in that case the nonlinear behaviour is because of intrinsic nonlinear processes (such as two photon absorption) and requires a minimum optical input power. In contrast, the feedback based electro-optic microdisk resonator described here is independent of the incident optical power and can be controlled by voltage feedback gain. Moreover, the optical quality factor of semiconductor microrings is $<10^5$, whereas quality factors above 10^6 are easily achievable in $LiNbO_3$ microdisks.

The combination of high quality factor and power-independent nonlinearity makes the $LiNbO_3$ microdisk bistable switch an excellent candidate for many optical signal processing applications previously explored using other approaches [6, 8]. Of particular interest is two wavelength all-optical switching where the probe signal is controlled by the pump signal via a nonlinearity [8]. In this configuration, the pump signal modifies the resonant frequency in the vicinity of the probe wavelength so that the optical output power at the probe wavelength may be controlled by the amount of power at the pump wavelength. In previous approaches, the pump signal should be strong enough to affect the probe signal through the nonlinear optical processes in, for example, a semiconductor. However, all-optical switching in a $LiNbO_3$ electro-optic microdisk bistable resonator is achievable even with low pump powers because the

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nonlinearity is induced by an externally tunable feedback. Such an electronically controllable nonlinearity adds an extra degree of freedom to switch design that enables hybrid electronic and optical signal processing.

Microdisk resonators with diameters <200 μm have been demonstrated [9]. These are potential candidates for hybrid integration. Silicon micromachining techniques (originally developed for integrated circuits and MEMS devices) could be employed to build features for mounting the microdisk as well as coupling elements to create an integrated version of the microdisk bistable switch. Furthermore, the idea of optical switching based on electro-optic WG resonators could be implemented in active monolithic WG resonators such as semiconductor and polymer microrings [10, 11].

4 Conclusion

In conclusion, we have shown experimentally strong nonlinear electro-optic behaviour of a $LiNbO_3$ microdisk resonator with voltage feedback. Simulation results confirm the physical origin of the behaviour. Future applications include all-optical switching and optical signal processing.

5 Acknowledgments

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