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Ring resonator-based photonic microwave receiver modulator with picowatt sensitivity

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Abstract: The authors report an enhanced $LiNbO_3$ microdisk photonic microwave receiver modulator with a sensitivity of 3 pW (-85 dBm) and a bandwidth of 60 MHz centred at 14.6 GHz. The sensitivity of the modulator is improved by using a critically coupled microwave ring resonator and a modified ground plane for passive *E*-field amplification and confinement.

1 Introduction

Electro-optic modulators are an essential part of most microwave photonic systems. They have been fabricated using a variety of electro-optic materials (polymer, semiconductor, crystalline). However, because of its superior optical, mechanical and electro-optical properties, $LiNbO_3$ is still the preferred active medium for electro-optic modulation. Conventional travelling wave Mach–Zehnder $LiNbO_3$ modulators are relatively large and power hungry. In order to overcome these deficiencies, electro-optic modulation using high-Q Whispering–Galley modes (WGMs) of a microdisk optical cavity has been proposed and demonstrated as an alternative approach [1–5]. In a resonant electro-optic microdisk modulator the electric and optical fields are simultaneously in resonance. The microdisk optical resonator confines the high-Q WGMs in a small-mode volume ($<10^{-3}$ mm^3), whereas a microwave resonator distributes the resonantly enhanced electric field along the optical path of WGMs. The high quality of the optical resonance in the microdisk modulator results in a relatively large effective interaction length and consequently enables efficient modulation in a small volume. An optically resonant modulator may modulate light within a small bandwidth ($\sim\nu_0/Q_L$, where Q_L is the loaded optical quality factor and ν_0 is the optical frequency) centred around modulation frequencies $f_{mod} = m \times \Delta\nu_{FSR}$, where m is an integer and $\Delta\nu_{FSR}$ is the free-spectral range of the optical resonator [2]. Despite this apparent limitation, resonant modulators are very useful in applications where high sensitivity in a narrow bandwidth is needed around a large centre frequency. For example, it has been shown that a $LiNbO_3$ microdisk modulator may be used in photonic microwave front-end design [3, 5], radiofrequency(RF)-over-fibre digital links [6] and opto-electronic oscillators [7]. Moreover, the non-linearities in the electro-optic response function of a microdisk modulator can be used to make all-optical microwave receivers [8, 9]. Although the centre modulation frequency of $LiNbO_3$ microdisk receivers has been extended to Ka-band and its sensitivity has been improved using large optical quality factors [10], less effort has been spent on enhancing the strength of electro-optic interaction by optimising the microwave *E*-field distribution around the microdisk. Previously extra sensitivity has been accompanied by a bandwidth penalty (e.g. 5 MHz for 0.1 nW sensitivity at 35 GHz [10]). Here we demonstrate that the sensitivity of a microdisk photonic microwave receiver may be significantly improved by modifying the properties of the microwave resonator without sacrificing the modulation bandwidth.

2 Modified microdisk modulator

In a resonant electro-optic modulator the efficiency of modulation is proportional to the electro-optically induced phase shift at each roundtrip (ϕ_{EO}) multiplied by the photon lifetime, τ_p. Photon lifetime (τ_p) is proportional to Q_L, whereas ϕ_{EO} is proportional to the strength of the microwave *E*-field, the overlap between optical and microwave fields and their relative phase velocity. In a microdisk modulator, the microwave *E*-field is distributed around the optical path using a microwave resonator that also passively amplifies the *E*-field. In the presence of simultaneous microwave and optical resonance, the microwave-optical phase-matching condition reduces to frequency matching between eigenfrequencies of the microwave resonator (f_{res}) and $m \times \Delta\nu_{FSR}$. However, to achieve frequency matching the *E*-field is usually distributed over a fraction of the optical path [1, 3, 5]. In early work, the fundamental resonant mode of a semi-ring RF resonator has been used for distribution and amplification of the *E*-field [1–4]. The semi-ring electrode is a standing-wave resonator with open ends, so that its resonant frequency can be easily tuned by changing its length. This property has made the semi-ring the preferred microwave resonator in most microdisk modulator designs. The roundtrip electro-optic phase shift with a semi-ring ($\phi_{EO,S}$) is maximum when its length (S) is exactly $L/2$ (where $L = \pi D$ is the perimeter of the microdisk) and the fundamental mode (f_{res}) is excited. So for a semi-ring, if S/L changes to a value other than 1/2 the modulation efficiency decreases. Alternatively, with careful design a full-ring ($L = S$) resonator can improve the efficiency by modulating the entire optical path length [11]. If the frequency of the fundamental mode of the full-ring resonator is matched to $\Delta\nu_{FSR}$, the resulting electro-optic phase shift per round trip ($\phi_{EO,R}$) is two times larger than that of the optimised semi-ring ($S = L/2$). Note that for low-order microwave modes the RF wavelength, λ_{RF} ($= c/n_{RF}f_{RF}$, $n_{RF} = \sqrt{\varepsilon_{RF}}$, where ε_{RF} is the effective permittivity of the microwave mode, c is the speed of light and f_{RF} is the frequency of the modulating field), is not small enough (compared with ring circumference: $2\pi R$) for resonant travelling wave operation. So, similar to the semi-ring resonator, the ring resonator is a standing wave resonator. Fig. 1 shows the normalised roundtrip electro-optic phase shift ($\phi_{EO}/\phi_{EO,R}$) plotted against (L/S) for $f_{res} = \Delta\nu_{FSR}$. Note that $f_{res} = c/Ln_R$ for the full ring and $f_{res} = Nc/2Ln_R$ for semi-rings ($N = L/S > 2$). The inset shows the variation of the standing wave voltage amplitude on the microwave resonator for $N = 1$, 2, 3 and 6.

The microwave resonance passively amplifies the input voltage and the voltage amplification factor ($G_V = V_{res}/V_{in}$) is proportional to $\sqrt{Q_{RF}}$, where Q_{RF} is the loaded quality factor of the microwave resonator [12]. Maximum resonant amplification of the input field occurs when the resonator and the microstripline that feeds the resonator are critically coupled (external and intrinsic quality factors of the microwave resonator are equal). In the linear regime and for a phase-matched microdisk modulator ($f_{RF} = f_{res} = \Delta\nu_{FSR}$), the modulated optical power ($P_{o,mod}$) is related to the input voltage amplitude (V_{in}) and input optical power ($P_{o,in}$) through

$$P_{o,mod} = \left(\frac{\eta_{EO}}{2}\Delta\lambda_{DC}G_V\frac{Q_L}{\lambda_o}\eta_{cop}\right)V_{in}P_{o,in} \qquad (1)$$

Here, η_{cop} is the fibre-to-fibre optical coupling efficiency, η_{EO} is the normalised roundtrip electro-optic phase shift ($\phi_{EO}/\phi_{EO,R}$) and λ_0 is the resonant optical wavelength. $\Delta\lambda_{DC}$ is the optical resonant shift when a DC voltage of 1 V is applied on the full optical path length around the microdisk. Note that the electro-optical overlap factor, the effect of microdisk thickness and its electro-optic coefficient as well as the effect of ground plane geometry on the strength of the E-field around the equator are all embedded in $\Delta\lambda_{DC}$. As shown in (1), for a phase-matched modulator the factor $\eta_{EO} \times \Delta\lambda_{DC}$ translates the DC-shift to the microwave response. In our modified design, we have enhanced the modulation efficiency ($P_{o,mod}/P_{o,in}$) by: (i) using a modified ground plane that improves $\Delta\lambda_{DC}$, (ii) a phase-matched full-ring resonator ($\eta_{EO} = 1$) instead of semi-ring ($\eta_{EO} \leq 0.5$) and (iii) critical coupling between the ring resonator and the microstrip line that maximises G_V. This has improved the experimentally measured sensitivity of the microdisk-based microwave photonic receiver by a factor of 30 compared to the best-reported sensitivities [3, 10].

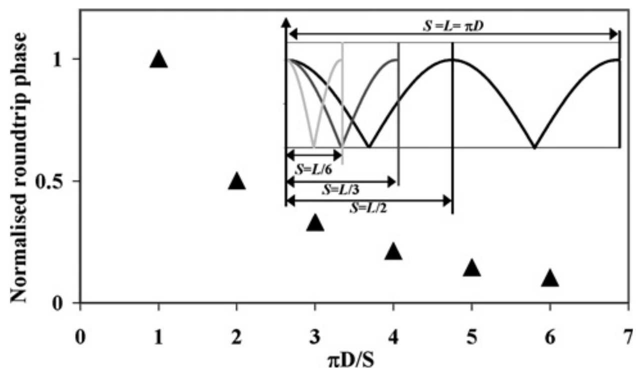

Fig. 1 *Normalised roundtrip electro-optic phase shift, $\phi_{EO}/\phi_{EO,R}$, plotted against the ratio between microdisk circumference and microwave resonator length ($\phi_{EO,R}$ is the roundtrip electro-optic phase shift for a full ring)*

Inset shows spatial distribution of resonant voltage amplitude on the microwave resonator for $L/S = 1$, 2, 3 and 6

3 Experiment

Fig. 2*a* is the top-view photograph of the modulator. The system uses a 410 µm-thick $LiNbO_3$ microdisk of 2.99 mm diameter and $\Delta\nu_{FSR}$ of 14.65 GHz. The optical source is a tunable single-mode laser with a linewidth of less than 500 kHz and relative intensity noise (RIN) of < -145 dBc/Hz. The microwave resonator is a copper ring with a diameter of 3 mm, width of 0.35 mm and thickness of 0.1 mm. The ring resonator is side-coupled to an open-ended 50 Ω microstripline that is fed through an SMA connector. The microdisk is mounted on a cylindrical ground plane with a diameter about 50 µm smaller than the ring resonator (Fig. 2*c*). The cylindrical ground plane enhances the strength of the E-field around the microdisk

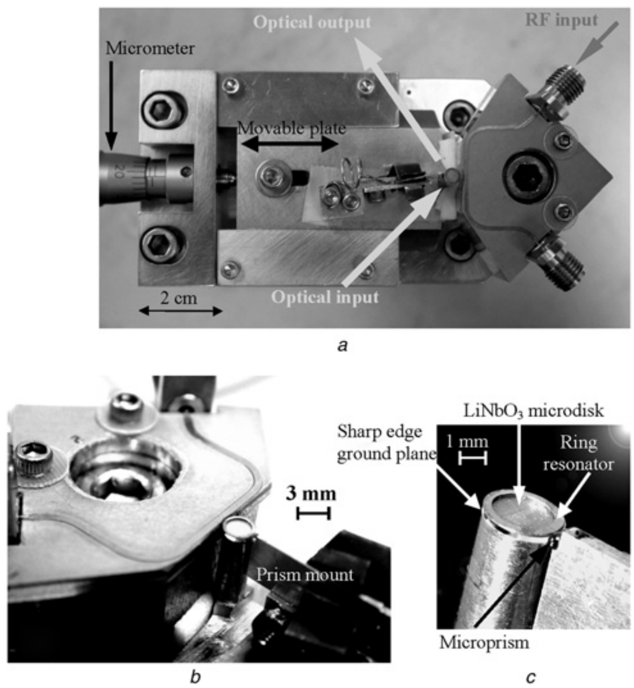

Fig. 2 *Photograph of the ring resonator-based photonic microwave modulator*

a Top-view photograph of the modulator configuration
b Close-up view of the $LiNbO_3$ microdisk with tunable microwave coupling gap
c $LiNbO_3$ microdisk mounted on the cylindrical ground plane

(compared to a large planar ground) by concentrating the field lines into its sharp edge. The cylindrical base (and therefore the microdisk/microring) can move relative to the microstripline using a micrometer (Fig. 2*b*). The coupling gap between the microring and microstripline can be controlled with 10 μm accuracy. Using this degree of freedom we have been able to critically couple the ring resonator and the microstripline. The measured value of $\Delta\lambda_{DC}$ is 0.13 pm/V. This is 30% larger than its value with a planar ground plane. The fundamental even resonance of the ring (f_{res}) is matched to $\Delta\nu_{FSR} = 14.6$ GHz. The effective microwave propagation constant ($2\pi n_{RF}/\lambda_{RF}$) of the ring is reduced using a thick electrode and creating an overhang above the microdisk (similar to techniques used in a Mach–Zehnder modulator). Fig. 3 shows the measured $|S_{11}|^2$ and $|S_{21}|^2$ for the microstripline side coupled to the RF ring resonator. The gap size (g) has been tuned such that at $\Delta\nu_{FSR}$ the fundamental even mode of the ring is critically coupled to the microstripline ($|S_{11}|^2 = |S_{21}|^2 = -6$ dB). The inset shows the simulated voltage distribution on the ring for the fundamental even mode. The measured loaded-Q_{RF} is 130 corresponding to an unloaded-Q_{RF} of 260. Note the radiation loss is less for a ring resonator compared to open-ended semi-ring resonators; therefore Q_{RF} is generally larger for a ring resonator. The maximum voltage amplitude on the ring is six times larger than the voltage amplitude on the microstripline ($G_V = 6$). The optical power is coupled into and out of the microdisk using a diamond microprism. The fibre-to-fibre optical insertion loss is about 10 dB. The loaded quality factor (Q_L) of the optical WGM selected for this experiment is about 3×10^6 corresponding to an RF modulation bandwidth of about 60 MHz (centred at 14.6 GHz). The laser input power in this experiment is about 1 mW (corresponding to 100 μW of detected optical power) and the laser wavelength is near 1550 nm. Fig. 4 shows the normalised detected microwave power plotted against input RF power. The detected power is normalised to the saturation microwave power (∼−10 dBm) at which the linear portion of the optical resonance is completely modulated. The dynamic range of this microwave-optical-microwave converter is 70 dB. Fig. 5 shows the spectrum of the detected microwave power at −70 dBm microwave input power. As may be seen even in the sub-nanowatt

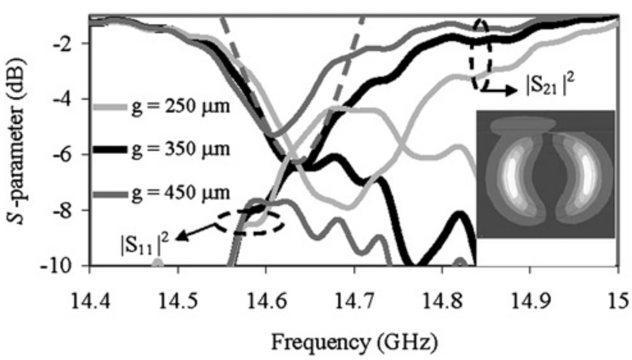

Fig. 3 *Measured S-parameters* $|S_{11}|^2$ *and* $|S_{21}|^2$ *for a ring resonator at different values of the gap size (g). The dashed line is the Lorentzian fit to the* S_{21} *spectrum in the critically coupled care*

At g = 350 μm the critical coupling ($|S_{11}|^2 = |S_{21}|^2 = -6$ dB) and RF-optical frequency matching ($f_{RF} = \Delta\nu_{FSR} = 14.65$ GHz) are achieved simultaneously. At g = 250 μm and the resonator is over-coupled and at g = 450 μm is under-coupled. The inset shows the voltage distribution on the ring for the fundamental even mode

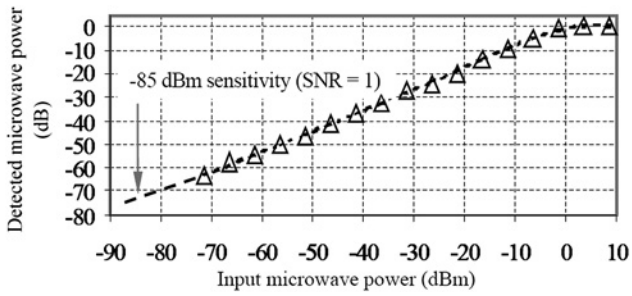

Fig. 4 *Detected RF power at 14.6 GHz (normalised to linear modulation saturation power) plotted against input power*

Optical intensity modulation is detected using an amplified photodetector with a responsivity of 260 μV/μW

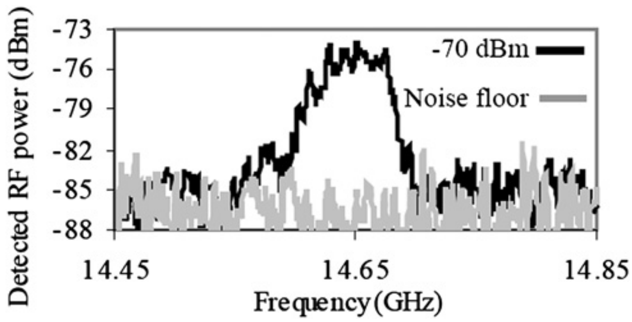

Fig. 5 *Spectrum of the detected RF power at −70 dBm RF input power (measured with a resolution bandwidth of 3 kHz)*

regime a signal-to-noise ratio (SNR) of about 10 dB and bandwidth of about 60 MHz is obtained. The minimum detectable RF power (SNR = 1) is −85 dBm (3 pW). This is a factor of 30 improvement compared to the previously reported results [3, 10]. Note that the microdisk used in this experiment is 2.6 times thicker than the microdisk used in [3] and four times thicker than the one used in [10]. Also the loaded optical-Q in this experiment is 1.5 times smaller than the Q_L in [3] and twelve times smaller than Q_L in [10]. So the sensitivity improvement is solely because of improved microwave design in this modulator (larger ϕ_{EO} and G_v). Theoretically using the microdisk employed in [10], our design could result in a sensitivity of better than −110 dBm with 1 mW optical input power.

4 Conclusion

We have improved the sensitivity of the electro-optic microdisk modulator by optimising the *E*-field distribution around the microdisk. Here we have shown that a critically coupled frequency-matched ring resonator with a cylindrical ground plane can enhance the modulation efficiency because of improved overlap between optical and microwave fields, larger electro-optic interaction length, stronger microwave field because of greater Q_{RF}, microwave critical coupling and use of a cylindrical ground plane.

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