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Mb/s data transmission over a RF fiber-optic link using a $LiNbO_3$ microdisk modulator

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Abstract

For the first time, we demonstrate data transmission over a radio frequency (RF) fiber-optic link using a $LiNbO_3$ microdisk configured to modulate an optical carrier. Initial experimental results demonstrate high-quality data transmission up to 100 Mb/s on a 8.7 GHz RF carrier.

Keywords: $LiNbO_3$ microdisk resonator; Optical modulator; Optical communication

1. Introduction

Recently a new microphotonic radio frequency (RF) receiver with direct electrical-to-optical conversion was proposed [1]. The receiver uses an electro-optic disk to modulate an optical carrier with the received RF signal. The modulator is configured as a traveling-wave resonator that can support very high-Q TE-polarized optical whispering-gallery modes (WGMs). The modulating electric field is provided by a separate RF-resonator whose frequency is tuned to the free-spectral-range (FSR) of the optical modes in such a way that it is in simultaneous resonance with the traveling optical waves inside the disk. It has been shown [2] that, unlike Mach–Zhender designs, the microdisk can perform efficient optical modulation without use of a reference arm to convert phase to amplitude modulation. Spatial confinement of the photon field, long photon lifetime inside the optical-resonator, and voltage gain provided by the RF-resonator can dramatically enhance RF-photon interaction (via the electro-optic effect) resulting in power-efficient RF-to-optical conversion in a small volume.

Previous work has focused on demonstration of single-frequency microwave and mm-wave modulation [2]. In this paper we report the first experimental results of Mb/s data transmission over a RF fiber-optic link using a microdisk modulator.

2. Experimental results

The disk employed is z-cut $LiNbO_3$ of radius $R = 2.56$ mm and thickness $t = 400$ μm. A microprism couples laser light into the microdisk and another prism is used to couple light out. A lens focuses light from a frequency stabilized tunable laser into the input-prism and a cleaved fiber at the output-prism collects and spatially filters the optical output. All components are mounted on a planar substrate. Fig. 1(a) shows a photograph of the experimental arrangement and Fig. 1(b) is a schematic diagram of the RF-optical link.

A half-ring metal electrode RF-resonator tuned to match the optical FSR = 8.68 GHz is placed on top of the disk to provide the resonant RF electric field. A RF carrier is modulated by a non-return-to-zero pseudo-random bit-stream (NRZ 2^7-1 PRBS) using a RF mixer and the signal feed is side-coupled to the resonator

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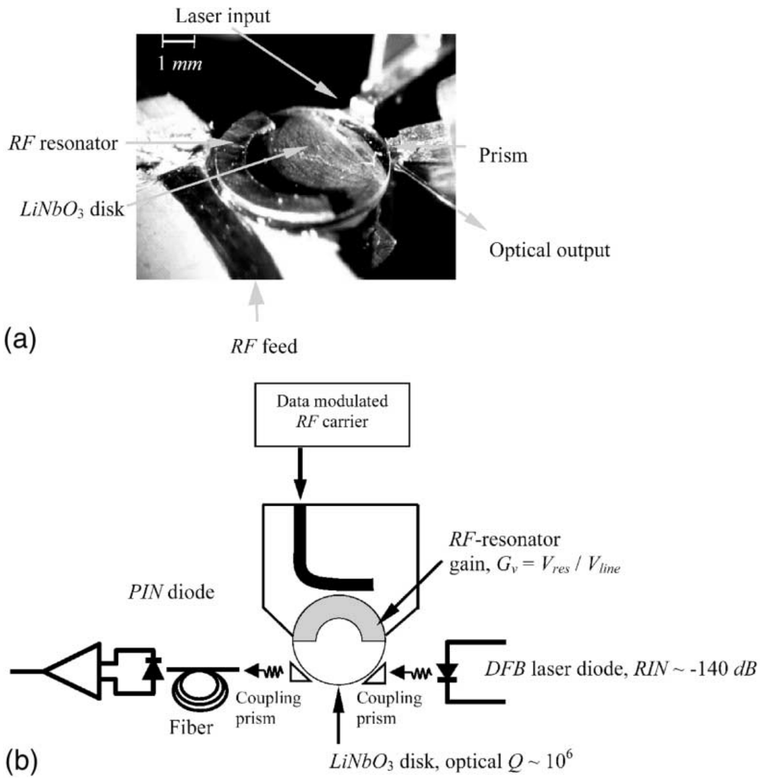

Fig. 1. (a) Photograph of the experimental arrangement. (b) Schematic diagram showing different parts of the RF optical-link.

electrode. The modulated optical carrier at frequency $f = 194$ THz (wavelength $\lambda = 1550$ nm) is transmitted through several meters of fiber and a PIN diode is used to detect and mix the optical signal. The integrity of demodulated data is measured using a bit error ratio (BER) tester and a digital oscilloscope. The laser wavelength is tuned close to one of the high-Q TE-modes of the disk where optical modulation is maximized. The bandwidth of a typical optical-mode is about 150 MHz, corresponding to an optical $Q = 1.3 \times 10^6$, and this limits the data transmission rate to <200 Mb/s.

Modulated RF power is measured within a 150 MHz bandwidth centered at 8.68 GHz RF-carrier frequency. Fig. 2(a) shows the measured phase-margin of the detected output at 10 Mb/s (NRZ 2^7-1 PRBS) data rate for the indicated modulated RF-power. The inset is representative of the corresponding input and output eye-diagram. Fig. 2(b) shows the RF signal spectrum before (left) and after (right) optical modulation. Fig. 2(c) shows the measured sensitivity of BER as a function of RF power. The optical output power for all of these measurements is in the range 18–27 μW and the laser wavelength is tuned close to the maximum slope of the optical mode.

Fig. 3 shows input and demodulated output eye-diagrams transmitted over the RF fiber-optic link at (a) 50 Mb/s and (b) 100 Mb/s NRZ 2^7- 1 PRBS data rates. The critical factors for high-quality data transmission are the purity and Q-factor of the optical mode, the magnitude of the rising or falling slope of the optical mode in the vicinity of the laser wavelength, and the optical output power from the disk. By tuning the laser wavelength and RF carrier frequency it is possible to optimize the modulation quality and efficiency. Due to the presence of high-Q (1–3×10^6) optical modes, the sensitivity of modulation quality and efficiency to the mode slope, wavelength stability of the laser is also important. To ensure stable, high-quality, data transmission the wavelength stability should be <0.1 pm.

3. Noise and BER performance

3.1. The model

To analyze performance of the microdisk modulator we use a model based on the fact that the transmissivity of a high-Q microdisk optical resonator in the frequency domain is a series of Lorentzian line-shapes, centered at the resonant frequencies (f_m) of the disk. For each mode the FWHM $= f_m/Q$ and $f_m = mc/2\pi R n_e$ where R is the

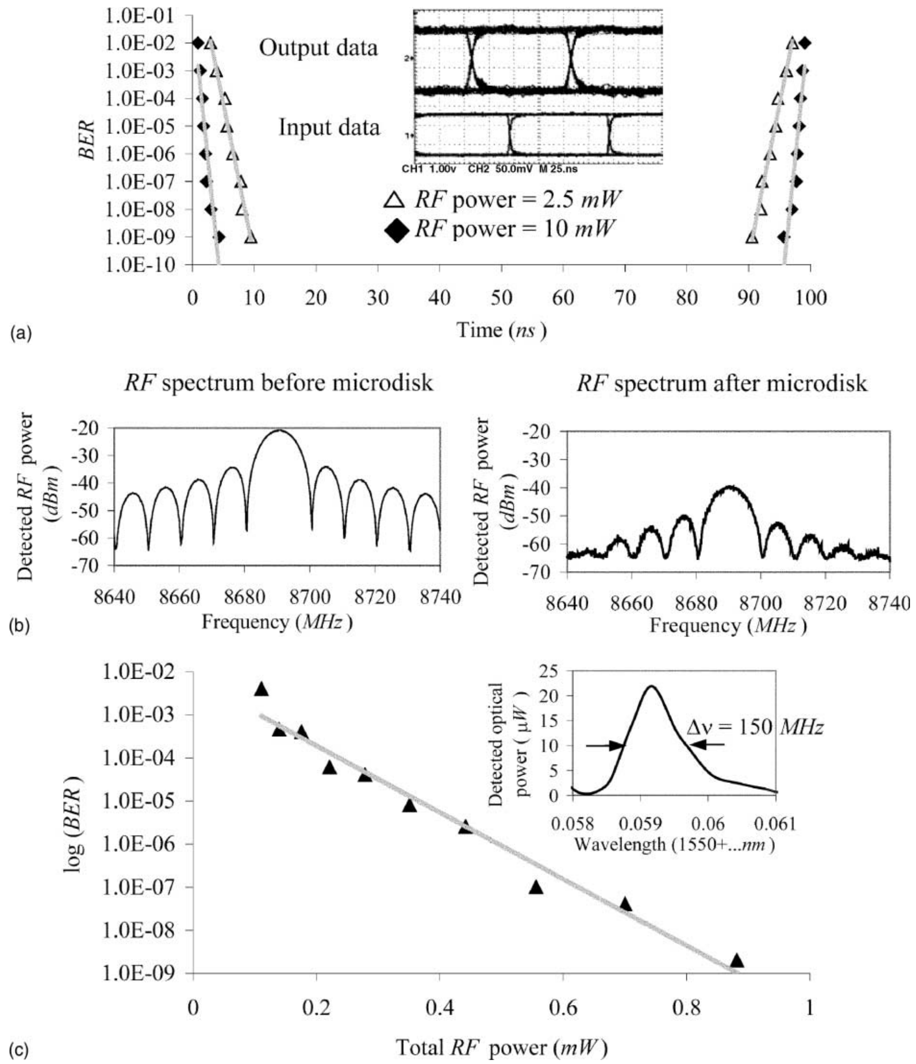

Fig. 2. (a) Measured phase margin of the output at 10 Mb/s (NRZ 2^7- 1 PRBS) for 10 and 2.5 mW modulating RF power. The inset shows representative input and output eye-diagrams. (b) Measured RF signal spectrum before and after microdisk modulator using 2.5 mW RF power. (c) Measured sensitivity of BER to modulating RF power (measured RF power within 150 MHz bandwidth centered at 8.68 GHz). The inset is the detected optical output power against input laser wavelength.

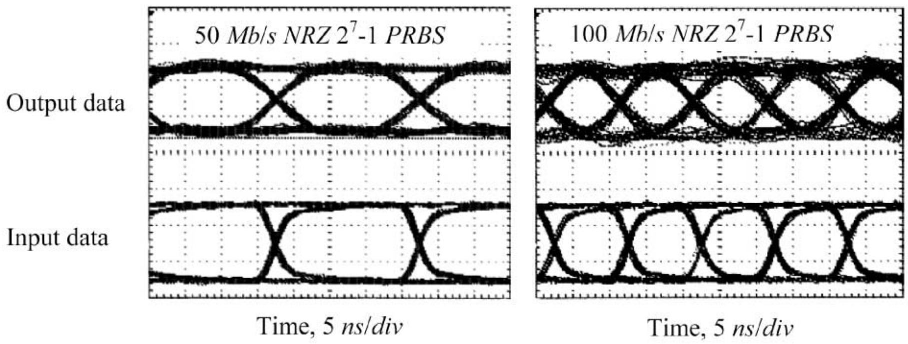

Fig. 3. Optical output eye-diagrams at 50 and 100 Mb/s (NRZ 2^7- 1 PRBS). The modulating RF power is 40 and 60 mW respectively.

disk radius, n_e the extraordinary refractive index of $LiNbO_3$, c is the speed of light in free-space, and m is the mode index. The electric field changes the refractive index of the disk via the electro-optic effect and therefore shifts the spectral position of the optical resonances. The efficiency of electro-optic interaction between optical WGMs and the applied electric filed is proportional to the optical interaction time and electric field intensity. The photon life-time inside the disk τ_{phot} is simply related to the slope of the Lorentizian via optical $Q \approx f\tau_{phot}$. Using this approach it is obvious that for constant RF-power modulation is maximum when the input optical wavelength is located at the slope maximum of the optical resonance. For a Lorentzian lineshape the slope maximum occurs at frequency f_0 when the optical output is about 75% of its peak value. Through the modulation process optical power is coupled out of frequency f_0 into optical side bands $f_0 \pm f_{RF}$. However, only RF frequencies within about $\Delta f_m = f_m/Q$ (near 100 MHz for an optical $Q = 1.5 \times 10^6$) and centered at integral multiples of the optical FSR ($f_{FSR} = c/2\pi R n_e$) are able to modulate the optical carrier.

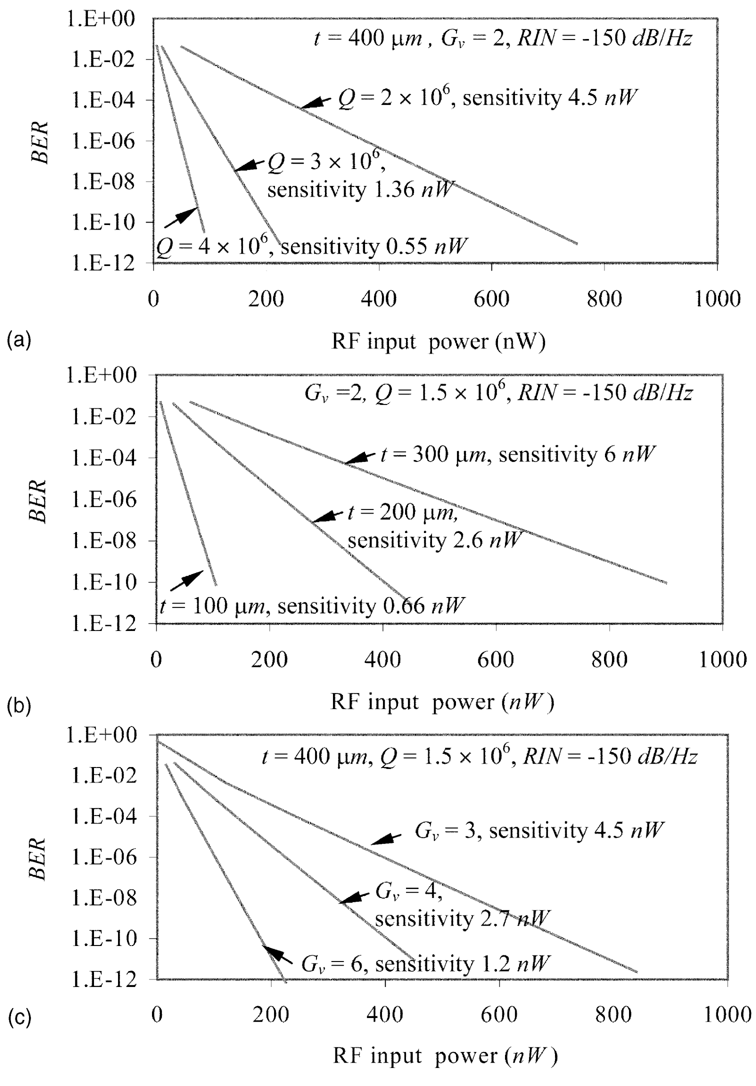

Fig. 4. BER calculations as a function of RF input power for different optical Q-factor, disk thickness, and voltage gain factor. In all cases optical coupling efficiency is 15%, RIN is −150 dB/Hz, optical input power is 5 mW, detector responsivity is 0.8 AW, detector dark current is 10 nA, temperature is 300 K, detector impedance is 10 kΩ and detector amplifier noise-figure is 3 dB. The sensitivity is defined as the RF-power at which the SNR is unity. (a) Effect of optical Q-factor on BER performance. (b) Effect of disk thickness on BER performance. (c) Effect of RF resonator voltage gain factor on BER performance.

The voltage developed on the resonator, V_{res}, may be estimated as a function of RF input voltage, V_{line}, on the microstrip line. The RF-electrode, which is side-coupled to the line, has a voltage gain ($G_v = V_{res}/V_{line}$) proportional to its Q-factor. Knowing the physical specification of the disk (Q, t, R, n_e), RF-resonator gain G_v, optical coupling efficiency, optical input power and wavelength one may calculate the optical modulation amplitude as a function of RF input power.

3.2. Noise sources and critical parameters

Noise in the system is conveniently ascribed to either optical or electrical sources. The optical sources are laser relative intensity noise (RIN) and detector noise (thermal and shot noise). The electrical sources are the microstrip, RF-resonator, and amplification stages used after detection. A noise model may be used to estimate the performance of an ideal RF-optical link. We use BER and sensitivity as a measure of link performance. Our simulations show that critical parameters strongly influencing BER are optical Q-factor, disk thickness, RF resonator voltage gain, and optical input amplitude fluctuations (laser RIN).

3.3. Results

Fig. 4 shows simulation results for a RF-optical-link with direct detection. The BER is calculated as a function of RF input power for different optical Q-factors, disk thickness, and voltage gain, G_v. In all cases the assumptions are 5.13 mm *disk* diameter, RIN = −150 dB/Hz, 15% optical coupling efficiency, 5 mW optical input power, 0.8 A/W detector responsivity, 10 nA detector dark current, 300 K temperature, 10 kΩ detector impedance, and a 3 dB detector amplifier noise-figure. Sensitivity is defined as the RF-power at which the signal-to-noise ratio is unity (SNR = 1). In Fig. 4(a) the effect of optical Q-factor on BER performance is demonstrated for $t = 400$ μm and $G_v = 2$. As may be seen, increasing optical Q by a factor of two improves sensitivity by a factor of eight. Fig. 4(b) shows the effect of reducing the disk thickness for $G_v = 2$ and $Q = 1.5 \times 10^6$. Reducing the disk thickness increases the electric field intensity. In more advanced simulations G_v may be calculated as a function of RF coupling factor, the geometry of the resonator and input RF power. Fig. 4(c) shows the effect of increasing G_v on BER performance for $Q = 1.5 \times 10^6$ and $t = 400$ μm.

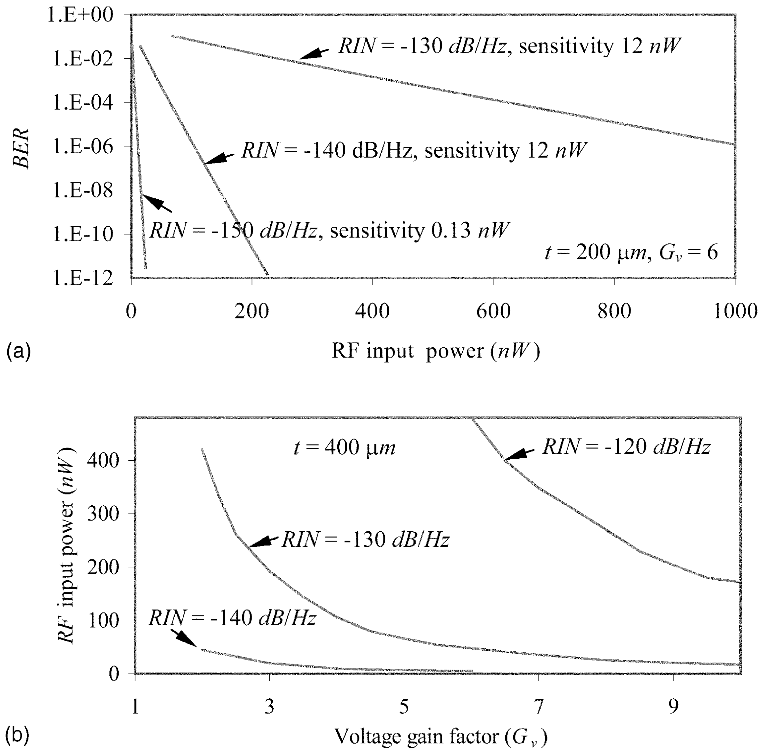

Fig. 5. Calculated influence of laser RIN on BER and sensitivity ($Q = 2 \times 10^6$ and other parameters are the same as Fig. 4). (a) BER performance with different values of RIN as a function of RF input power. (b) Sensitivity with different values of RIN as a function of G_v.

Fig. 5(a) illustrates how laser RIN can influence BER. In this case $G_v = 6$, $t = 200$ μm and $Q = 2 \times 10^6$. With a value of RIN $= -140$ dB/Hz and $G_v = 6$ it is possible to achieve a BER around 10^{-10} with 200 nW RF input power. Fig. 5(b) shows it is possible to reduce the impact on sensitivity of noise generated due to laser RIN by increasing voltage gain G_v in the system. The results shown in Fig. 5(b) are obtained using $t = 400$ μm and $Q = 2 \times 10^6$. Increasing voltage gain by a factor of five can be equivalent to reducing RIN by 10 dB/Hz.

4. Conclusion

In conclusion, we have demonstrated high-quality data transmission at Mb/s data rates over a RF-optical link using a new microdisk optical modulator. The modulator is able to efficiently modulate an optical carrier at $\lambda = 1550$ nm wavelength with a data modulated RF signal. By tuning the laser wavelength to a high-Q optical mode 10 Mb/s NRZ 2^7-1 PRBS data was successfully transmitted through a RF fiber-optic link with a measured BER of $<10^{-9}$. We have also demonstrated clean eye-diagrams may be achieved at 50 and 100 Mb/s rates. Calculations show nW sensitivity may be achieved by simply reducing disk thickness, increasing RF-resonator voltage gain, and reducing laser RIN.

Acknowledgements

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