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Solid-State Electronics 49 (2005) 1428–1434

SOLID-STATE ELECTRONICS

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Self-homodyne RF-optical $LiNbO_3$ microdisk receiver

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Received 31 May 2005; accepted 9 June 2005

The review of this paper was arranged by Prof. C. Tu

Abstract

A novel RF-optical receiver architecture based on *nonlinear* optical modulation in a $LiNbO_3$ microdisk modulator is presented. This is the first RF-optical receiver without high-speed electronic components for transmitted carrier links. We demonstrate receiver operation by demodulating 50 Mb/s digital data from a 8.7 GHz carrier frequency.

Keywords: RF-optical receiver; Self-homodyne; Nonlinear modulation; $LiNbO_3$ microdisk modulator

1. Introduction

In homodyne and super-heterodyne RF receiver architectures local oscillators (LOs) and mixers are used to down-convert and extract the baseband information from the received RF signal. Due to a desire for reduced part counts, size, weight and power consumption in high-carrier frequency short distance applications, self-homodyne and self-heterodyne systems have been proposed [1,2]. In a self-homodyne and self-heterodyne transmission system the transmitter broadcasts a RF modulated signal *and* the local carrier so the baseband/IF signal can be down-converted by mixing the received carrier and modulated signal in a nonlinear device (i.e., a self-mixer). The receiver power consumption, phase noise, and complexity are reduced by eliminating the LO and the mixer. Although such an approach suffers from reduced power efficiency, it has been shown that it can lower overall cost and complexity in mm-wave local area networks and indoor wireless transmission systems [1]. In this paper we demonstrate that the second-order nonlinearity of an optical microdisk modulator, biased at its maximum transmission point, may be used to realize the mixing process required to extract the baseband signal from the transmitted carrier RF signal.

2. Self-homodyne RF-optical receiver

A self-homodyne RF-optical receiver replaces the function of a single-ended diode or FET mixer in a transmitted carrier wireless link with a sensitive optical modulator that performs down-conversion in the optical domain. In this approach the nonlinear dependence of transmitted optical power (P_o) on applied RF voltage (V_{RF}) is the source of nonlinearity in the system. Fig. 1 illustrates the block diagram of the self-homodyne RF-optical receiver. The received RF signal that contains both sidebands and the center frequency (transmitted-carrier double-sideband modulation format) is fed to an optical modulator biased at its nonlinear operating

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0038-1101/$ - see front matter
doi:10.1016/j.sse.2005.06.008

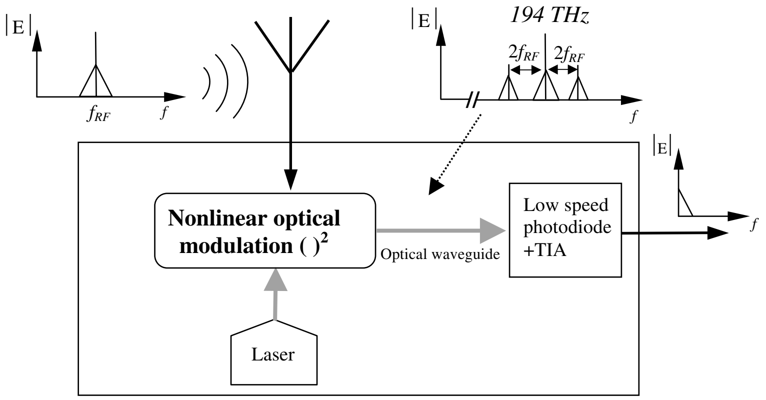

Fig. 1. RF-optical receiver architecture. The transmitted carrier received microwave signal nonlinearly modulates the laser light in optical modulator. The baseband intensity modulation is generated as a result of carrier-sideband mixing in optical domain. Finally optical output is fed to a low-speed photodetector for baseband detection.

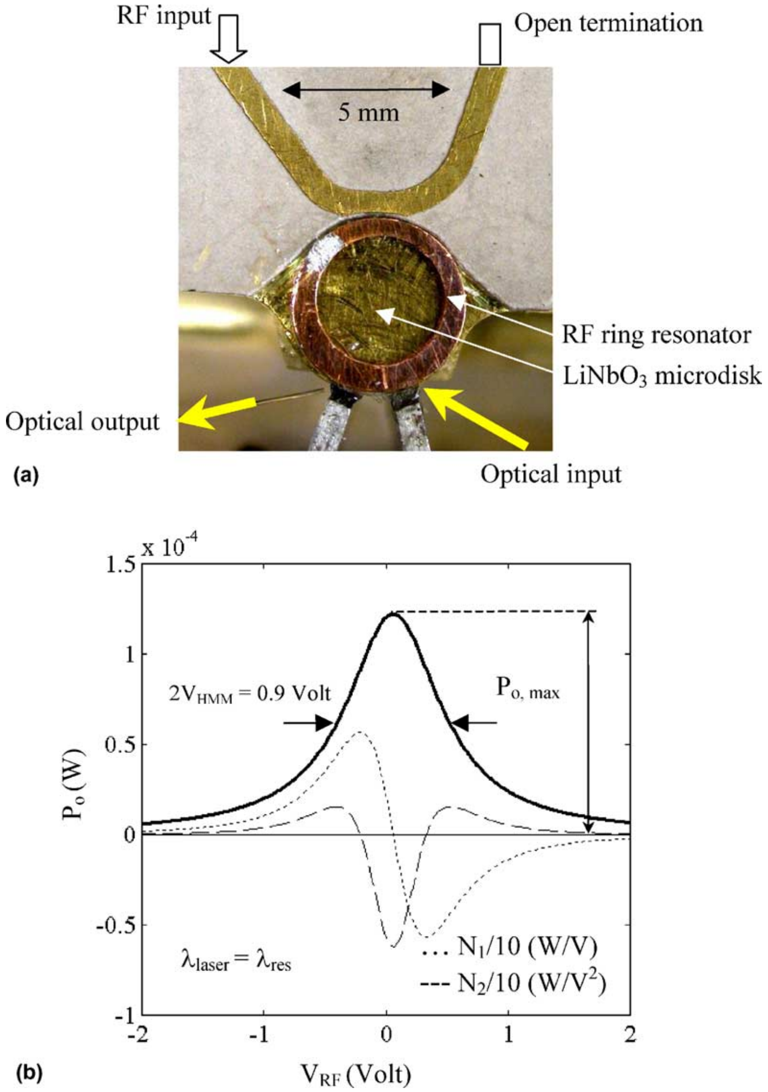

Fig. 2. (a) Photograph of a $LiNbO_3$ microdisk modulator with two prism couplers and the ring resonator. (b) The simulated optical output power of a typical $LiNbO_3$ microdisk modulator as a function of input RF voltage. The dashed and dotted lines are generated as the first and second Taylor coefficients in an expansion of the optical transfer function (solid line).

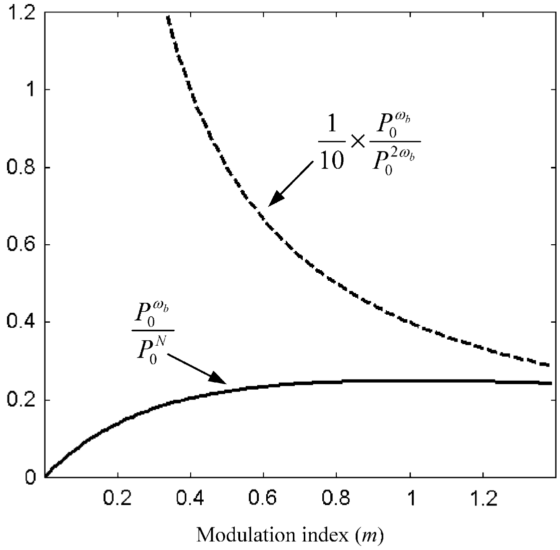

Fig. 3. The variation of the baseband modulated optical power at ω_b relative to modulated optical power at $2\omega_b$ (dashed line) and total nonlinear modulated power (solid line), against m.

point. The carrier and sidebands are mixed through the second-order nonlinearity; hence, the optical output intensity spectrum contains the baseband and high-frequency products around the second-harmonic of the carrier frequency. A photoreceiver with a bandwidth matched to the baseband signal detects and automatically filters out the high-frequency components. In this way, the bandwidth of electrical circuitry used in the system is limited to that of the baseband signal. The efficiency of a RF-optical receiver strongly depends on the sensitivity of the optical modulator and the magnitude of its second-order nonlinearity. Given that most wireless links only require a limited bandwidth around a high frequency carrier, a microdisk modulator is a suitable choice for this application since it fulfills both criteria when biased at maximum optical transmission.

The key elements of a self-homodyne photonic receiver are a laser, a microdisk modulator and a photoreceiver. The laser should have a linewidth of about 100 times smaller than the microdisk linewidth. Its wavelength should be stable enough so that a feedback circuit can be used to lock the laser wavelength to the maximum transmission of an optical resonance using a DC bias on the microdisk. Today's DFB laser technology can easily provide high efficiency, desired stability and linewidth at a low price. The photoreceiver is a low-price slow-speed digital photoreceiver with enough sensitivity to detect the baseband modulated optical power at minimum received RF power. The relative simplicity and small number of components employed in such a receiver may reduce the size and cost of the receiver especially at high carrier frequencies.

Typically, a microdisk modulator has a very high sensitivity within a limited bandwidth centered at frequencies equal to integral multiples of the optical free spectral range (FSR) [3]. Even in a nonoptimized 700 μm thick $\mathrm{LiNbO_3}$ microdisk modulator, we have observed a signal to noise ratio (SNR) of 13.5 dB with applied microwave power of −56 dBm (2.5 nW) at 7.6 GHz [4], which corresponds, to a sensitivity (SNR = 1) of −68 dBm (158 pW). Ilchenko et al. have reported a 150 μm thick microdisk modulator with a SNR of 14 dB when excited by −56 dBm RF power at 9.15 GHz [6].

The optical transfer function of the microdisk modulator has a Lorentzian shape around each resonant wavelength (λ_{res}) with a loaded optical-Q ($Q = \lambda_0/\Delta\lambda_{\mathrm{FWHM}}$) limited by optical coupling factor (κ_0) and the distributed internal loss (α). The modulating voltage across the optical mode is created by an RF ring resonator [4] with a voltage gain G_{v} at resonance [5]. Fig. 2(a) is a photograph of the $\mathrm{LiNbO_3}$ modulator configuration. The optical power from a tunable laser is fed by fiber to a lens system that focuses laser light through a microprism and couples the light to the microdisk. A second prism couples out the optical power that is fed by a second fiber to an optical receiver. Fig. 2(b) shows the simulated optical output power of a typical $\mathrm{LiNbO_3}$ microdisk modulator as a function of input RF voltage (notice that the actual interacting RF voltage seen by the optical mode is larger due to electrical resonance). The laser wavelength (λ_{laser}) is tuned to an optical resonance of the microdisk so in the absence of an external voltage the transmitted optical power is maximized. The sensitivity of the modulator can be quantified by a voltage amplitude V_{HMM} that modulates half of the maximum transmitted power ($P_{\mathrm{o,max}}$). V_{HMM} is determined by the optical-Q, disk thickness (t_{d}), the electro-optic coefficient (r_{33}) and G_{v}. In our simulation the modulator parameters are chosen to be representative of the experimental values: $Q = 4 \times 10^6$ (corresponding to optical mode loss factor $\alpha = 0.014$ and optical coupling factor $\kappa_0 = 0.08$), $t_{\mathrm{d}} = 400$ μm, $G_{\mathrm{v}} = 6$ V, $V_{\mathrm{HMM}} = 0.45$ V and input optical power = 1 mW.

We can expand the electro-optic transfer function $P_{\mathrm{o}}(V_{\mathrm{RF}})$ around $V_{\mathrm{RF}} = 0$ as

$$P_{\mathrm{o}} = N_0 + N_1 V_{\mathrm{RF}} + N_2 V_{\mathrm{RF}}^2 + \cdots, \tag{1}$$

where $N_i\,(i > 0)$ is the ith Taylor expansion coefficient of $P_{\mathrm{o}}(V_{\mathrm{RF}})$ at $V_{\mathrm{RF}} = 0$ and N_0 is the maximum transmitted optical power ($P_{\mathrm{o,max}}$). When the modulator is biased at its extreme nonlinear operation regime $\lambda_{\mathrm{laser}} = \lambda_{\mathrm{res}}$ and $V_{\mathrm{RF}} < V_{\mathrm{HMM}}/4$ (small signal regime), the behavior of P_{o} can be estimated as $P_{\mathrm{o,max}} + N_2 V_{\mathrm{RF}}^2$. The dotted and dashed lines in Fig. 2(b) are the calculated N_1 and N_2 coefficients for the simulated transfer function (solid line). As one may see, around the transmission peak $|N_2| \gg N_1$ and the modulator is effectively operating as a square-law detector. At a given voltage the value of N_2 is proportional to V_{HMM} and $P_{\mathrm{o,max}}$.

If the baseband is a pure sinusoidal signal, the received RF voltage can be expressed as

$$V_{\mathrm{RF}} = V_0(1 + m \cdot \cos(\omega_{\mathrm{b}}t))\cos(\omega_{\mathrm{RF}}t), \tag{2}$$

where m is the RF modulation index, ω_{b} is the baseband frequency and ω_{RF} is the RF carrier frequency. In the pure nonlinear modulation regime ($\lambda_{\mathrm{laser}} = \lambda_{\mathrm{res}}$) the transmitted optical power can be written as

$$\begin{aligned} P_{\mathrm{o}} &= P_{\mathrm{o,max}} + N_2 \times V_{\mathrm{RF}}^2 \\ &= P_{\mathrm{o,max}} + N_2V_0^2(1 + m \cdot \cos(\omega_{\mathrm{b}}t))^2\cos^2(\omega_{\mathrm{RF}}t). \end{aligned} \tag{3}$$

Expanding the second term on the right hand side of Eq. (3) one obtains a DC term equal to $(N_2V_0^2/2)(1+m^2/2)$, high-frequency components centered around $2\times\omega_{\mathrm{RF}}$ given by

$$\frac{N_2V_0^2}{2}\left(\left(1+\frac{m^2}{2}\right)\cos(2\omega_{\mathrm{RF}}t)+\left(\frac{m^2}{4}\right)\cos^2(2\omega_{\mathrm{b}}t) \times \cos(2\omega_{\mathrm{RF}}t)+m\cos(\omega_{\mathrm{b}}t)\cos(2\omega_{\mathrm{RF}}t)\right),$$

and two down-converted low frequency terms at ω_{b} and $2\omega_{\mathrm{b}}$ given by

$$\frac{N_2V_0^2m^2}{4}\cos(2\omega_{\mathrm{b}}t)+N_2V_0^2m\cos(\omega_{\mathrm{b}}t).$$

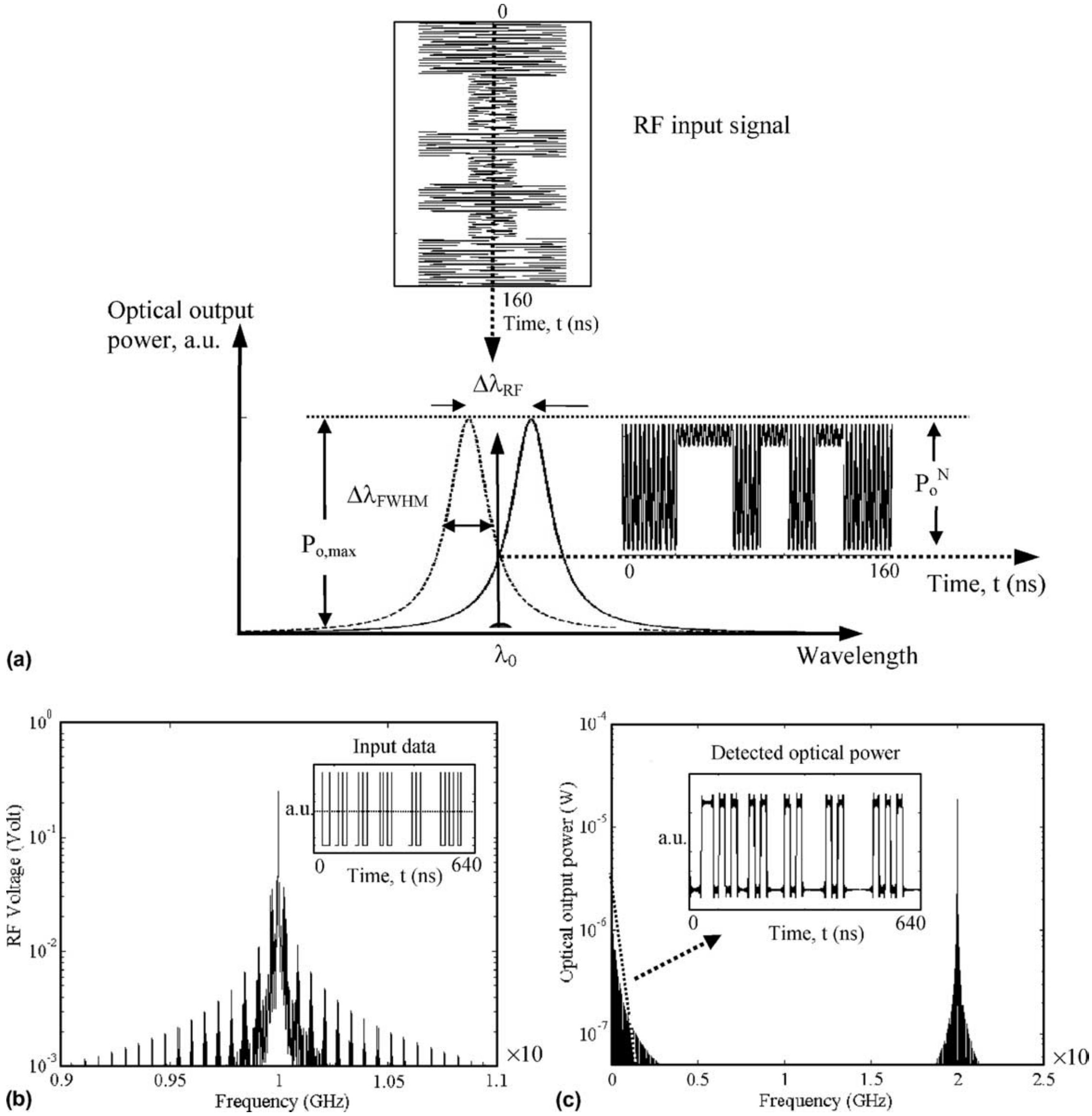

Fig. 4. The simulated signal flow in a microdisk RF-optical receiver. (a) Second-order nonlinear modulation in a microdisk modulator when the laser wavelength (λ_0) has been tuned to the peak of the transfer function. The input RF signal is a 10 GHz RF carrier modulated by a 62.5 Mb/s data stream. (b) The spectrum of transmitted-carrier RF signal. The inset shows the original data in a 640 ns time interval. (c) The spectrum of the optical output intensity after nonlinear modulation. The high-frequency components are filtered out by the photodetector bandwidth (dashed line) and only the baseband is converted to electric signal. The inset shows the detected data in the same time interval.

The total (nonlinearly) modulated optical power is

$$P_{\mathrm{o}}^{N} = \left|(1 + m^2 + 2m)N_2V_0^2\right|. \tag{4}$$

This is equivalent to the maximum amplitude of the second term in Eq. (3). Fig. 3 shows the variation of the baseband modulated optical power at ω_{b} relative to modulated optical power at $2\omega_{\mathrm{b}}$ (dashed line) and total nonlinear modulated power (solid line), against m. As may be seen the second-harmonic baseband term ($2\omega_{\mathrm{b}}$) may be suppressed relative to the baseband (ω_{b}) by employing a transmitted carrier RF modulation format ($m < 2$). In the small signal operating regime ($V_{\mathrm{RF}} < V_{\mathrm{HMM}}/4$), with a second-harmonic baseband suppression ratio of 10 dB ($m = 0.4$), the theoretical power efficiency of this down-conversion process is 20% corresponding to 20% of the total modulated optical power being modulated at baseband frequency. At peak optical transmission N_2 is negative so the down converted baseband signal is 180° shifted relative to the original signal. In a data link, we may use a digital photoreceiver to detect the baseband and simply recover the original data from the data bar port. Another possible solution is to use optical transmission dips (as opposed to peaks) and bias the microdisk at its minimum transmission point. Employing a transmission minimum can also minimize the DC component in the microdisk modulator output and reduce the laser noise contribution to the overall detected noise.

One may also use a Mach–Zehnder (MZ) modulator for mixing RF signals in the optical domain. Gopalakrishnan et al. have used the third-order nonlinearities of two cascaded MZ modulator biased at quadrature point [7]. At this bias point the magnitude of the RF signals should be comparable to V_{π} in order to generate detectable third-order nonlinear frequency components. Given the relatively large values of V_{π} this approach may not be feasible for wireless applications where the received RF power is very small. In contrast, using the maximum transmission point of a resonant microdisk results in a very sensitive square-law mixer that has large

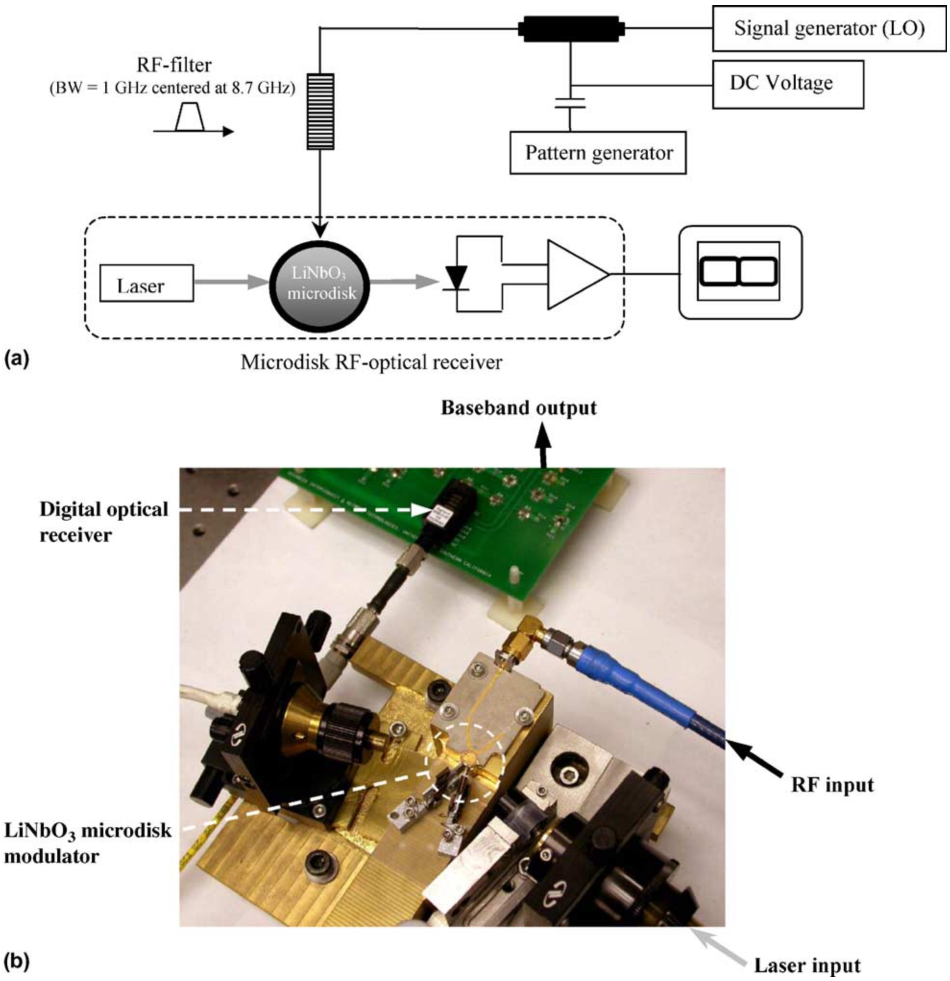

Fig. 5. (a) Schematic diagram of the experimental arrangement for demonstrating all-optical down-conversion with microdisk modulator. The carrier frequency is 8.7 GHz and it is modulated with data stream from the pattern generator. (b) Picture of the RF-optical receiver showing the microdisk modulator and the digital optical receiver.

second-order nonlinearity at small signal regime. Even if the MZ modulator is biased at the maximum transmission point, the large V_π and the cosine functionality of the electro-optic transfer function cannot compete with the high sensitivity of microdisk modulator and its Lorenzian transfer function.

The results of simulating the signal flow in the RF optical receiver are shown in Fig. 4. In this simulation the microdisk modulator parameters are the same as Fig. 2(b). Fig. 4(a) shows the modulated transfer function when the laser emission wavelength (λ_0) is centered at the peak of the microdisk optical resonance and the modulator is fed by the data modulated RF carrier. $\Delta\lambda_{\mathrm{RF}}$ is the amplitude of the resonant wavelength oscillation due to the applied RF voltage. Fig. 4(b) shows the spectrum of the transmitted-carrier RF input signal. The RF carrier frequency of 10 GHz is modulated by a 62.5 Mb/s data stream with modulation index of $m = 0.5$. The inset shows the original data stream in a short time interval (640 ns). Fig. 4(c) shows the calculated spectrum of the optical output intensity. Nonlinear modulation generates the baseband signal and high-frequency components around 20 GHz. The photodetector bandwidth (=0.1 GHz, dashed line) filters out the high-frequency components and only the baseband is converted to an electric signal. The inset shows the detected data stream again in a 40 ns time interval.

3. Experiment

The $\mathrm{LiNbO_3}$ microdisk used in experiments is 400 μm thick, 5.13 mm in diameter, and has an optical free spectral range of 8.7 GHz. A copper ring electrode on top of the microdisk with a resonant RF voltage gain of 5.5 at 8.7 GHz is used to create the electric field for

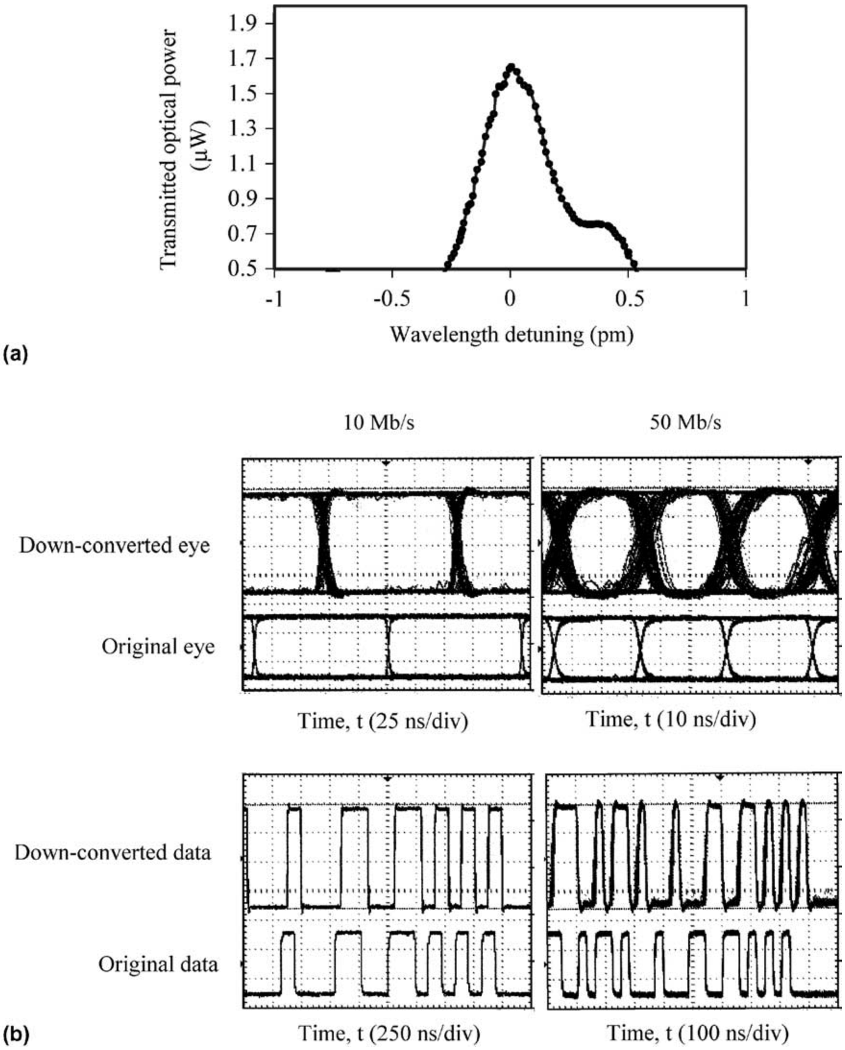

Fig. 6. (a) The optical mode selected for data down-conversion with a Q of 3.5×10^6. (b) Receiver eye-diagrams and demodulated data for $2^7 - 1$ PRBS data sequences at 10 Mb/s and 50 Mb/s rates after electro-optical down-conversion from 8.7 GHz RF carrier frequency. The measured bit error ratios are 10^{-9} (5.6 dBm RF input power) and 8×10^{-9} (9.5 dBm RF input power), respectively.

electro-optic modulation. The RF signal applied is an 8.7 GHz RF carrier mixed with the baseband signal in a double-balanced RF mixer. By DC-biasing the IF port of the mixer we can control the modulation index m and consequently the magnitude of transmitted power at the carrier frequency (in our experiment $m = 0.4$). The RF signal is applied to the microdisk modulator after passing through a bandpass RF filter (8.7 GHz center frequency and 1 GHz bandwidth) to ensure any nonlinear products of the oscillator and amplifier are filtered out. Fig. 5(a) shows a schematic diagram of the experimental arrangement and Fig. 5(b) of the RF-optical receiver showing the microdisk modulator and the digital receiver. Optical input to the microdisk modulator is provided by a tunable single mode laser with 0.3 pm wavelength resolution and <0.5 MHz linewidth. Optical output is detected using a digital photoreceiver with a sensitivity of −34.5 dBm and −3 dB bandwidth of 100 MHz. The measured Q of the optical mode is 3.5×10^6 and transmitted optical output power ($P_{\text{o,max}}$) is 1.8 μW. The laser wavelength ($\lambda_0 \approx 1550$ nm) is tuned to the optical resonator's peak transmission. Fig. 6(a) shows the optical resonance spectrum used in experiment. Fig. 6(b) shows the detected data and clean eye-diagrams after electro-optical down-conversion when the RF carrier is modulated by a pseudo-random bit stream (PRBS $2^7 - 1$) at 10 Mb/s and 50 Mb/s. The measured bit error ratios are 10^{-9} and 8×10^{-9}, respectively.

4. Conclusion

A novel self-homodyne RF-optical receiver has been described. Down-conversion occurs in the optical domain through *nonlinear* modulation, thereby eliminating the need for an RF local oscillator and mixer. Clean eye-diagrams at 10 Mb/s and 50 Mb/s are down-converted from a transmitted carrier RF signal with 8.7 GHz carrier frequency using a microdisk modulator.

The sensitivity of the microdisk modulator can be maintained up to mm-wave frequencies by increasing the optical FSR. This can be achieved by reducing the disk diameter. However the maximum data bandwidth will be limited by the optical-Q of the microdisk resonator. So the receiver has potential to be used in future indoor mm-wave wireless links where a finite bandwidth around a high-frequency carrier is desired.

Acknowledgements

This work is sponsored by *NSF*, *NASA* and *DARPA*.

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