Sub-MicroWatt Photonic Microwave Receiver

V. S. Ilchenko, A. A. Savchenkov, A. B. Matsko, and L. Maleki

***Abstract*—We report efficient photonic reception of nanowatt microwave signals by their direct upconversion into optical domain using high-Q whispering gallery modes in a millimeter size toroidal cavity fabricated from $LiNbO_3$.**

***Index Terms*—Electrooptic modulation, microresonators, microstrip resonators, microwave detectors, nonlinear optics, Q factor.**

I. Introduction

PHOTONIC front-end microwave receiver architectures have emerged as a new way of microwave and millimeter wave signal processing. Direct upconversion of the microwave signals into the optical domain by an electrooptic modulator (EOM) allows for application of simple optical processing methods, such as filtering and microwave frequency conversion based on photonic local oscillators (e.g., OEO [1]). In addition, photonic receivers hold promise for significant reduction in power consumption as compared with electronic microwave and millimeter-wave receivers [2].

Until recently, the potential for photonic receiver architectures was constrained by the lack of high-sensitivity EOMs. State-of-the-art commercial Mach–Zehnder modulators still require about 1 W of applied microwave power to achieve full modulation. Recently, a new kind of EOM and a microphotonic receiver based on interaction of light and microwaves in a nonlinear-optic whispering-gallery (WG) resonator combined with a miniature microwave cavity was suggested [3]–[6]. Preliminary experimental data with microwave sensitivity at the level of 160 μW were reported for such a device [6].

Here, we present the demonstration of a microphotonic receiver with orders of magnitude improved sensitivity. The minimal detectable microwave power of this device is 2.5 nW with about 14 dB signal-to-noise ratio (SNR), corresponding to the noise floor of ~0.1 nW and ~5 kHz analog bandwidth. Although the bandwidth of this device is narrower than those of electronic receivers [2], it has other advantages due to small power consumption and the simplicity associated with optical signal processing. This performance may be further enhanced by increasing the quality factors and improving the microwave and optical field overlap. Used as an EOM, our microwave receiver demonstrates high-efficiency light modulation with a small controlling microwave power (1 mW operational power and 10 mW full saturation).

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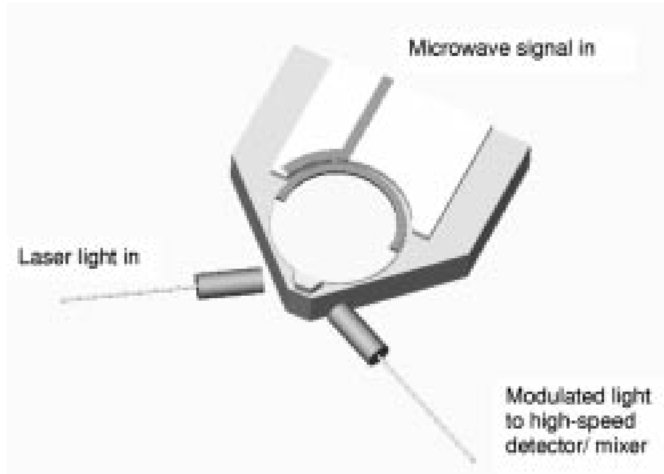

Fig. 1. Experimental setup.

II. Experiment

In our experiment, light from a distributed feedback (DFB) laser having 1550 nm wavelength is launched into Z-cut $LiNbO_3$ spheroidal optical cavity using a diamond prism (see Fig. 1). The light is tuned to have a frequency near a particular cavity mode. The input optical power is about 2 mW, and the output optical power detected is 10 dB less than the input power.

The cavity is a thin disk with radius 2.4 mm, thickness 150 μm, and with its perimeter edge polished into a toroidal geometry of transverse curvature diameter 180 μm. The crystal C axis of $LiNbO_3$ coincides with the symmetry axis of the cavity within 0.1° uncertainty. The loaded optical quality factor of WG modes is $Q \simeq 5 \times 10^6$ (optical resonance bandwidth 30 MHz).

The field confinement volume of the WG modes overlaps with that of a microwave resonator that is excited by a microstripline coupler delivering the input microwave signal. We used a half-wave microstrip cavity arranged by placing a half-circular electrode along the rim of the resonator to tailor the microwave field structure for optimal nonlinear-optic interaction. The quality factor of this microwave cavity is $Q_M = 120$, and the bandwidth ~80 MHz. By tuning the length of the stripline electrodes, the microwave cavity resonance frequency can be tuned to be equal to the optical free spectral range (9.155 GHz in our case).

We studied the dependence of light modulation as a function of frequency of the input microwave signal power in this device. The typical frequency response of the device is shown in Fig. 2. Here, the laser is constantly kept at the slope of the resonance curve of an optical mode, with the microwave frequency scanned, and the demodulated microwave power is obtained by a high-speed photodetector. This signal is recorded by a network

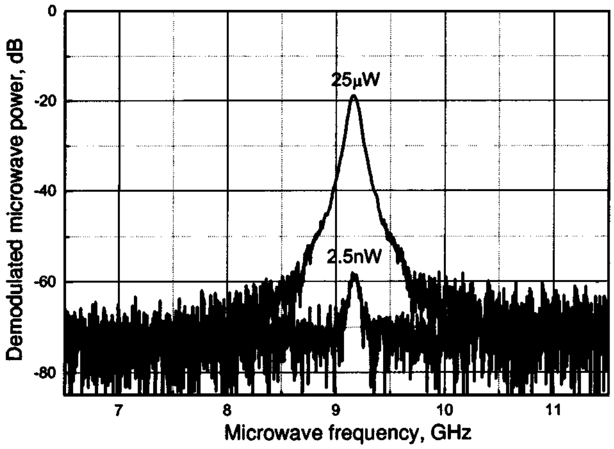

Fig. 2. Demodulated microwave power versus frequency of the microwave pumping. Zero level corresponds to the saturation power.

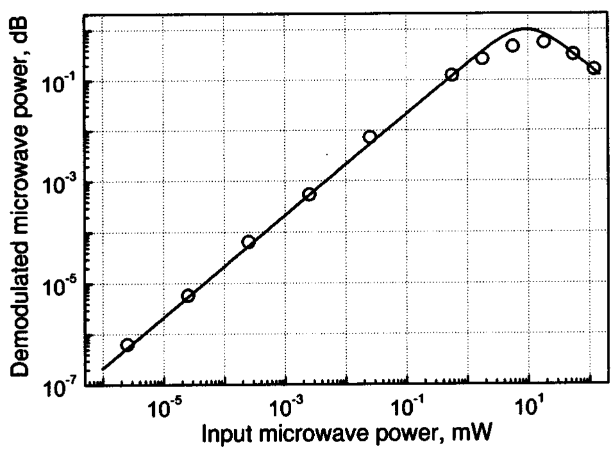

Fig. 3. Normalized demodulated microwave power versus power of the microwave pump. Experimental data are shown by circles. Theoretical simulations shown by the solid line.

analyzer. For the 2-mW laser used in the experiment, the absolute value of the demodulated signal power is 31 dB less than the input microwave signal power. The curves in Fig. 2 are well under the saturation limit shown by the 0-dB level. As follows from Fig. 2, the operational 3-dB bandwidth of our receiver is ~85 MHz.

The amplitude characteristics of our modulator/receiver were studied as the dependence of the demodulated microwave power obtained by a high-speed photodetector at the optical output of the modulator on the input microwave power. Results are presented in Fig. 3. The saturation point at ~10 mW corresponds to the limit imposed by harmonic multiplication, as well as power broadening, of the optical resonances. This shows that our photonic receiver can be used as an effective EOM. The optimal power within the linear regime of the modulator is about 1 mW, and the dynamic range of the receiver is ~70 dB.

This system may produce both phase and amplitude modulation signals. When the laser is tuned to the slope of the optical resonance, the modulation is mostly of the amplitude type. The modulation is of phase-type for the laser tuned to the center of the resonance. The dependence of the demodulated microwave power on the laser detuning from the optical resonance is shown in Fig. 4. Amplitude modulation is a maximum when the laser

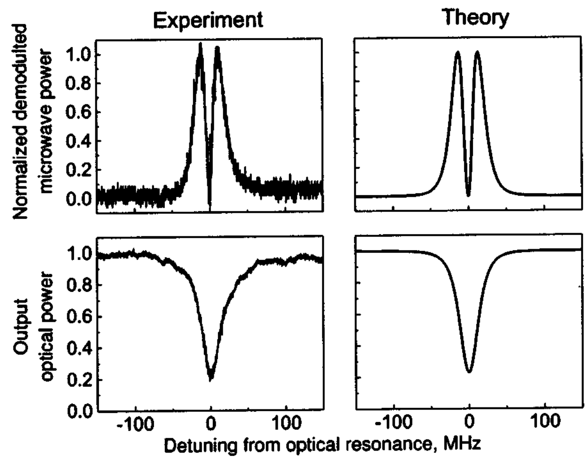

Fig. 4. Top: Demodulated microwave power (beat note of the output radiation having frequency ω_M) versus detuning of the pump light from the whispering gallery mode resonance. Bottom: Whispering gallery mode resonance. No signal is found for the resonant tuning. Theoretical dependence is found from steady state solution of (1)–(4).

is tuned to the slope of the resonance curve of WG mode curve and equals zero exactly at the optical resonance.

III. Theory and Discussion

To describe analytically the interaction between different optical modes, we assume that each mode can be considered independently. This assumption is valid when frequency splitting between the modes significantly exceeds mode bandwidth, which is usually the case for any high-Q mode of a cavity.

Let us consider the problem of nonlinear interaction of a single whispering gallery mode (A) pumped with a laser radiation having carrier frequency ω_0 and a microwave field mode (C) pumped with radiation having frequency ω_M. We study the generation of sidebands (B_- and B_+) having $\omega_0 - \omega_M$ and $\omega_0 + \omega_M$ frequencies.

Fields amplitudes inside the optical cavity and microwave resonator can be found from [8]

$$\dot{A} = -[i(\omega - \omega_0) + \gamma]A - ig^*(B_- C + C^\dagger B_+) + F_A \quad (1)$$

$$\dot{B}_- = -[i(\omega_- - \omega_0 - \omega_M) + \gamma]B_- - igC^\dagger A \quad (2)$$

$$\dot{B}_+ = -[i(\omega_+ - \omega_0 + \omega_M) + \gamma]B_+ - igCA \quad (3)$$

$$\dot{C} = -[i(\omega_c - \omega_M) + \gamma_M]C - igB_-^\dagger A - ig^* A^\dagger B_+ + F_M \quad (4)$$

where γ and γ_M are optical and microwave decay rates, respectively, and ω, $\omega_\pm$, and ω_c are the mode frequencies. The mode amplitudes are normalized such that $A^\dagger A$ gives the photon number in the pumping mode and the same for the other modes. The amplitudes of pumping terms F_A and F_M are determined as $|F_M|^2/\gamma_M^2 = 4W_M Q_M/(\hbar\omega_M^2)$ and $|F_A|^2/\gamma^2 = 4WQ/(\hbar\omega^2)$, where W and W_M are the input optical and microwave powers, respectively. The mode coupling constant can be introduced as

$$g = \frac{8\pi\omega}{\epsilon_a} d_{\text{eff}} \sqrt{\frac{2\pi\hbar\omega_c}{\epsilon_c \mathcal{V}_c}} \left[\frac{1}{\mathcal{V}} \int_{\mathcal{V}} d\mathcal{V} \Psi_a \Psi_b \Psi_c\right] \quad (5)$$

where $d_{\rm eff}$ is the electrooptic constant for the cavity material [8]; ϵ_a and ϵ_c are the dielectric susceptibilities for the optical and microwave frequencies; $\mathcal{V}$ is the whispering gallery mode volume; $\mathcal{V}_c$ is the volume of the microwave field; and Ψ_a, Ψ_b, and Ψ_c are the normalized dimensionless spatial distributions of the modes. Here, we assume that the whispering gallery modes are nearly identical, i.e., $\omega \simeq \omega_\pm \gg \omega_c$, $\mathcal{V} \simeq \mathcal{V}_\pm$, $\int d\mathcal{V}\Psi_a\Psi_{b-}\Psi_c = \int d\mathcal{V}\Psi_a\Psi_{b+}\Psi_c$.

Let us calculate the power of the output light for the harmonics ($W_\pm$) with respect to the pumping power ($W_{\rm in}$). For the sake of simplicity, we consider the entirely resonant case. Introducing such quality factors as $Q = \omega_0/(2\gamma)$ and $Q_M = \omega_M/(2\gamma_M)$ and recalling $|C|^2 = |F_M|^2/\gamma_M^2 = 4W_MQ_M/(\hbar\omega_M^2)$, we derive from (1)–(4)

$$\frac{W_\pm}{W_{\rm in}} = \left(\frac{2\mathcal{S}}{1+2\mathcal{S}^2}\right)^2, \qquad \mathcal{S} = \frac{4|g|Q}{\omega_0}\sqrt{\frac{W_MQ_M}{\hbar\omega_M^2}}. \quad (6)$$

It is easy to see from (6) that the performance of the system can be improved significantly by increasing mode quality factors and decreasing mode volumes.

Let us estimate the interaction constant from (5). Taking $\omega = 10^{15}$ rad/s, $\omega_c = 7 \times 10^{10}$ rad/s, $d_{\rm eff} = 4 \times 10^{-12}$ m/V = 1.6 $\times\ 10^{-7}$ CGS, $\mathcal{V}_c = 5 \times 10^{-5}$ cm^3, and the mode overlapping integral ∼0.5, we get $g = 140$ rad/s. In the experiment, we have a maximum frequency conversion ($\mathcal{S} = 2^{-1/2}$) for $W_M \approx 10$ mW, $Q_M \approx 100$, $\omega_M \approx \omega_c$, and $Q \approx 10^6$. This gives us $g \approx 125$ rad/s. The difference between measured and calculated values of constant g can be explained by the imperfect mode overlap, absorption in the system, and generation of additional harmonics that we did not take into account.

We have considered the interaction of light and microwaves leading to the generation of two optical harmonics. In general, multiple harmonic generation is possible when the cavity modes are equidistant and frequency difference between them is equal to the microwave frequency. The input–output ratio for the light in the all-resonant case (zero detunings) may be written as

$$E_{\rm out}(t) = \frac{1 - 2i\mathcal{S}\cos(\omega_M t + \phi_M)}{1 + 2i\mathcal{S}\cos(\omega_M t + \phi_M)}\,E_{\rm in}(t) \quad (7)$$

where ϕ_M is determined by the phase of the microwave pump. Therefore, an increase of the microwave power leads to the increase of the number of optical harmonics instead of the saturation and the decrease in the field amplitude, as with the simplified model. However, for small microwave powers, the three-mode approximation is good enough.

Finally, it has to be mentioned that other types of nonlinear interactions may be possible, which may potentially be detrimental to the functionality of a modulator in a small $LiNbO_3$ cavity such as ours. For example, parasitic acoustic excitations by the piezoelectric effect have been reported in conventional EOMs. Nevertheless, we have not observed any indication of these phenomena with our modulator within the full range of the applied microwave power. The unconventional geometry of our modulator prevents effective interaction of light and acoustic waves: In the area of modal overlap (perimeter of the resonator), acoustic modes are orthogonal to optical whispering-gallery modes, and even if excited, the strain modes induced in the material do not influence the light. The same conclusion is applicable to the Brillouin interaction: While usually limiting the performance of fiber-optic devices, it does not impose any serious restrictions in our case of WG mode optical cavity.

IV. Conclusion

We have discussed the experimental demonstration and theoretical analysis of a high-sensitivity microwave receiver based on high-Q whispering gallery modes. The modes are excited in a nonlinear dielectric resonator to efficiently mix light and microwave fields. We overcome restrictions normally imposed in such a configuration by phase-matching conditions by engineering the microwave resonator and a doubly resonant optical cavity.

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