Three-wave mixing with whispering-gallery modes for electro-optic modulation and photonic reception

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Abstract: We demonstrate an electro-optic microwave modulator with milliWatt control power and a sub-microWatt photonic receiver based on triply-resonant three-wave mixing in high-Q toroidal lithium niobate cavities with whispering-gallery (WG) modes.

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Mixing of fields with significantly different frequencies has many practical as well as fundamental applications. In most cases however, this interaction is either inhibited by phase mismatch, or requires strong fields to observe sizeable effects. We achieve effective mixing of weak microwave and light fields by engineering triple resonance phase matching and demonstrate a high-sensitivity microphotonic receiver as well as low-controlling power electro-optical modulator based on this interaction. Microwaves are applied via a cavity tuned to bridge the free spectral range between the optical whispering-gallery modes in a highly-oblate toroidal resonator of lithium niobate. Bipolar microwave field configuration compensates the orbital momentum mismatch between the photons in adjacent optical modes (Fig.1).

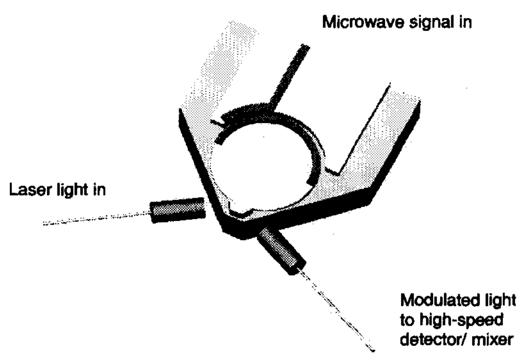

Fig. 1. Experimental setup. The cavity is a thin disk with radius 2.4 mm, thickness 150 μm, and with perimeter edge polished into toroidal geometry of transverse curvature diameter 180 μm. Crystal C-axis of $LiNbO_3$ coincides with the symmetry axis of the cavity within 0.1 degree uncertainty. The loaded optical quality factor of WG modes is $Q \simeq 5\times10^6$ (optical resonance bandwidth 30 MHz). The field localization area of optical WG modes overlaps with that of a microwave resonator that is excited by a microstripline coupler delivering the input microwave signal. To tailor the microwave field structure for optimal nonlinear-optic interaction, we used half-wave microstrip cavity arranged by placing a half-circular electrode along the rim of the resonator. Quality factor of such a microwave cavity is $Q_M = 120$ and the bandwidth $\sim$ 80 MHz. By tuning the length of the stripline electrodes, microwave cavity resonance frequency can be tuned to equal the optical free spectral range (9.155 GHz in our case).

The minimal detectable microwave power in our experiment is 2.5 nW with about 14 dB signal-to-noise ratio, corresponding to the noise floor at $\sim$ 0.1 nW, and $\sim$ 5 kHz analog bandwidth (Fig.2). Our electro-optical modulator demonstrates high efficiency light modulation with small controlling microwave power (1 mW operational power and 10 mW full saturation), orders of magnitude better than previously reported results [1, 2, 3, 4].

Amplitude characteristic of our modulator/receiver was observed 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. 2. Saturation point at $\sim$ 10 mW corresponds to the

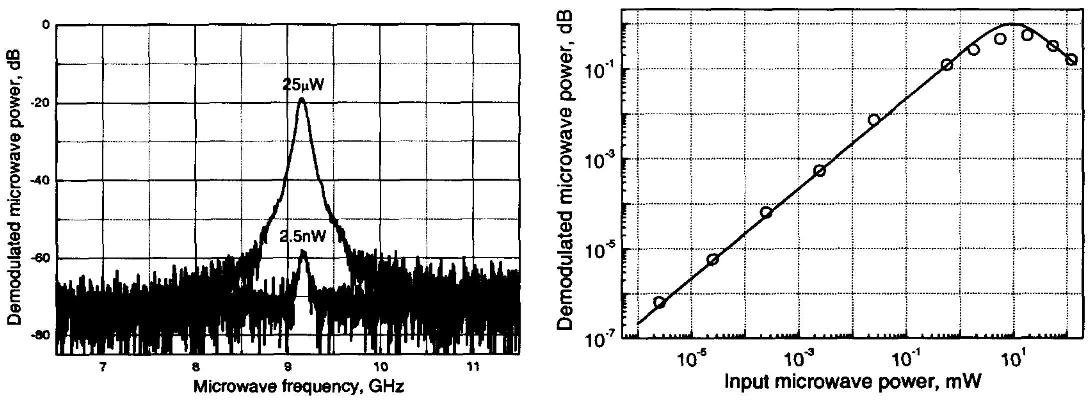

Fig. 2. Performance of microphotonic receiver. Left hand side: dependence of light modulation as a function of frequency of the input microwave signal power. The laser with 2 mW power and 1550 nm wavelength is constantly kept at slope of the resonance curve of an optical modes, the microwave frequency is scanned, and the demodulated microwave power produced by a high-speed photodetector at the end of the output optical fiber is recorded by a network analyzer. The curves are well under the saturation limit shown by zero dB level. The operational 3 dB bandwidth of our receiver is $\sim$ 85 MHz. Right hand side: saturation curve. Circles show experimental results, solid line – numerical simulations.

limit imposed by harmonic multiplication (Fig.3) as well as power broadening of the optical resonances. Optimal operational power within linear regime of the modulator is about 1 mW.

For the all resonant tuning the input/output relation for the light amplitude is

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

where

$$\mathcal{S} = 4Q\chi^{(2)}\sqrt{\frac{\pi W_M Q_M}{\omega_M \mathcal{V}_M}} \left[\frac{1}{\mathcal{V}} \int_{\mathcal{V}} d\mathcal{V} \Psi_a \Psi_b \Psi_c \right], \quad (1)$$

Q and Q_M are the optical and microwave quality factors, $\chi^{(2)}$ is the nonlinearity of the optical cavity material, W_M is the microwave power, ω_M is the microwave frequency that coincides with the free spectral range of the optical cavity, $\mathcal{V}$ and $\mathcal{V}_M$ are volumes of the optical and microwave modes, Ψ_i is a mode spatial profile, the expression in brackets is the modes' overlap integral.

The system produces both phase and amplitude modulation. When the pumping laser is tuned to the slope of the optical resonance, the modulation is mostly of the amplitude-type. The modulation is phase-type for the resonant laser tuning. The dependence of the demodulated microwave power on the pump laser frequency detuning from the optical resonance is shown in Fig. 4. Amplitude modulation is maximal when the laser is tuned to the slope of the resonance curve of WG mode curve, and equals to zero exactly at the optical resonance.

Apart from obvious photonic modulator and receiver applications of the novel device, we can theoretically predict interesting low-threshold optical parametric instability when Q factors and modal overlap are improved. With purely optical pumping, generation of two light modes with frequency difference equal to twice frequency of the microwave field will be possible, even with no microwave field applied. This process will resemble four-wave mixing processes in $\chi^{(3)}$ media, where Stokes and anti-Stokes fields are generated from a single coherent pump field. The threshold value for the optical pump power is

$$W_{th} = \left(\frac{1}{\chi^{(2)}}\right)^2 \frac{\mathcal{V}_M}{\pi Q_M} \frac{\omega_0}{4Q^2}, \quad (2)$$

where ω_0 is optical carrier frequency. If the overlap integral equals to 1/2, optical quality-factor $Q = 3 \times 10^7$, and the microwave $Q_M = 10^3$, with the realistic mode volume $\mathcal{V}_c = 10^{-7}$ cm^3 we obtain $W_{th} = 1$ μW.

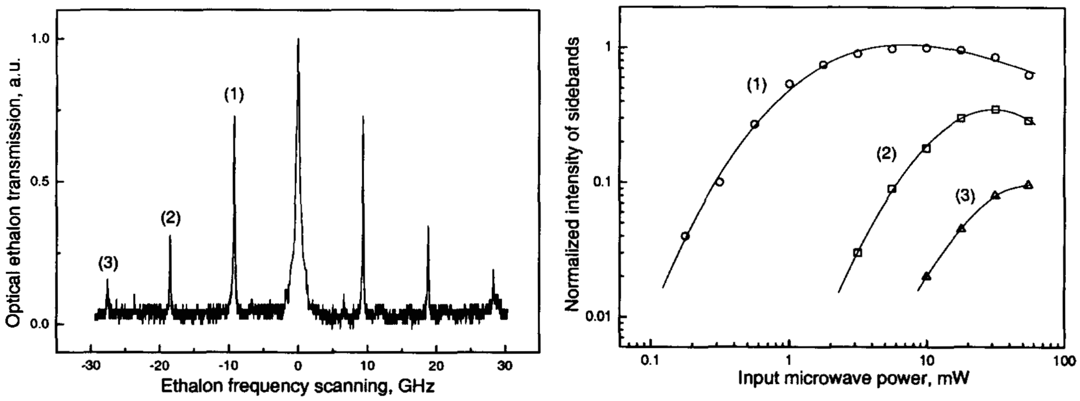

Fig. 3. Left hand side: Optical spectrum of the modulated signal obtained with scannable Fabry-Perot ethalon the pumping the system light. Right hand side: Normalized power of optical harmonics generated in the modulator vs power of the microwave pump. The unity power corresponds to the maximum power of the first harmonic measured in our experiment.

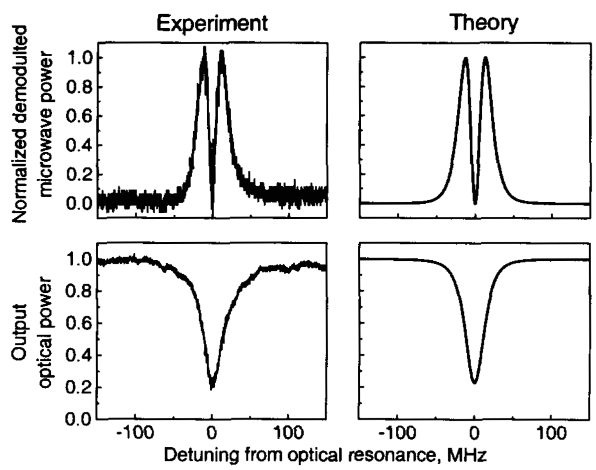

Fig. 4. Top: Demodulated microwave power vs detuning of the pump light from the whispering gallery mode resonance. Bottom: Whispering gallery mode resonance. No signal is found for the resonant tuning.

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