Coherent resonant Ka-band photonic microwave receiver

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Abstract: We propose theoretically and demonstrate experimentally a coherent microwave photonic receiver operating at 35 GHz carrier frequency. The device is based on a lithium niobate or lithium tantalate optical whispering gallery mode resonator coupled to a microwave strip line resonator. Microwave local oscillator is fed into the microwave resonator along with the microwave signal. We show that the sensitivity of this receiver significantly exceeds the sensitivity of the incoherent quadratic receiver based on the same technology. The coherent receiver can possess a dynamic range in excess of 100 dB in 5 MHz band if a low noise laser is utilized.

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1. Introduction

Direct microwave receivers based on all-resonant interaction of light and microwaves in solid-state whispering gallery mode (WGM) resonators have been recently developed [1]-[12]. The sensitivity of such devices does not degrade with the increasing microwave frequency. Phase insensitive (direct) $X-\nu$, $K_u-\nu$, and $K_a-\nu$-band WGM-based receivers have been demonstrated previously [1]-[12]. In this paper we present results of our experimental and theoretical study of phase sensitive (coherent) WGM-based microwave photonic receivers operating in the $K_a-\nu$-band. We show that such a device has a lot of promise compared with its phase insensitive analogies. We first briefly describe the results of our experimental studies, and then address the theoretical issues related to the coherent receiver.

The receiver operates due to three-wave mixing occurring in the resonator host medium possessing a quadratic nonlinearity. A microwave signal along with a microwave local oscillator (LO) is sent into the resonator pumped optically (Fig. 1). The RF modulation frequency of the microwave carrier cannot exceed the spectral width of both the optical and microwave resonances. The pump light interacts with the microwaves creating optical harmonics when the carrier frequencies of the signal and LO coincide with the integers of the free spectral range (FSR) of the WGM resonator. Each harmonic is spectrally separated from the optical carrier by a value equal to a linear combination of the signal and local oscillator frequency. The nonlinear process also changes the transmission of the optical carrier. Information about the microwave signal is retrieved by means of processing and detecting the optical sidebands and/or the optical carrier leaving the resonator.

![Fig. 1. Scheme of the coherent receiver.](image)

2. Experiment

In our experiment the lithium niobate WGM resonator with 35 GHz FSR was excited using 1550 nm laser light at the resonant frequency of one of the optical TE modes (the electric field is parallel to the resonator symmetry axis which coincides with the c-axis of LiNbO$_3$). The laser frequency is kept at the center of the optical resonance. The light output of the resonator received at a low frequency photodetector reproduced the product of the low frequency signal
and the LO, both applied to the resonator. We have applied 10 kHz to 100 kHz signals modu-
lated on the 35 GHz microwave carrier as well as a DC LO detuned 50 kHz to 500 kHz from
the signal carrier frequency to the resonator. A couple of examples of the detected signal are
shown in Fig. (2).

![Graph](image)

**Fig. 2.** The coherent receiver baseband response. The optical coupling efficiency is ap-
proximately 60%, and the optical insertion loss away of the WGM resonance is less than
3 dB. The input optical power of the receiver does not exceed 50 $\mu$W. The signal pulses
have 0.4 nW power and 20 $\mu$s duration. Their carrier frequency is approximately 35 GHz
(FSR of the WGM resonator). Microwave local oscillator (LO) has 10 $\mu$W DC power and
50 kHz (a) [100 kHz (b)] detuning from the signal carrier frequency. There is no time aver-
aging of the response. The fringes occur due to interference of the LO and the signal. The
sensitivity of the receiver corresponding to SNR=1 is better than 0.1 nW. The dynamic
range is better than 50 dB. The bandwidth of the receiver is given by the optical linewid-
th of the WGMs and is approximately 5 MHz. Measurement bandwidth (scope) is 20 MHz.
The gain of the receiver $G$ is equal to 0.01. It is evaluated from the data assuming the de-
tector resistance $\rho_{pd} = 10 \text{ kOhm}$ and amplitude of the retrieved signal $V = 0.35 \text{ mV}$. The
power of the measured noise approximately corresponds to the thermal noise power in the
bandwidth of the measurement.

The operation principle of the coherent receiver is based on the RF modulation of the reso-
ant absorption of the pumping light when both the microwave signal and LO are present. A
critically coupled resonator absorbs all the input resonant light, and the spectrum of the modes
of a critically coupled resonator has 100% contrast. When a microwave LO is applied to the res-
onator the excited WGM resonance broadens and the light coupling efficiency decreases [4][12].
First of all, the LO results in generation of the optical sidebands that escape the resonator and
show overall increase of the optical power on the slow photodiode. Microwave signal applied
to the same resonator results in time dependent change of the efficiency of the optical coupling.
The time dependent change of the optical power transmitted through the resonator is propor-
tional to the product of the amplitudes of the signal and the LO. Hence, the photocurrent created
by the light exiting the resonator depends on the relative phase of the LO and the signal as well
as on the amplitudes of the signal and the LO.
3. Theory

Let us theoretically study the receiver properties. We consider the nonlinear interaction of a WGM having resonant frequency $\omega_0$ and pumped with resonant light, as well as a microwave field mode having frequency $\omega_{mw}$ and pumped with radiation having frequency $\omega_M$. We study the generation of multiple Stokes and anti-Stokes sidebands as the result of the nonlinearity in the resonator medium, having $\omega_0 - l\omega_M$ and $\omega_0 + l\omega_M$ frequencies, where $l$ is an integer number. In what follows we consider only the lowest sideband order $l = 1$, neglect by the dispersion of the resonator, and assume that the microwave frequency $\omega_M$ is nearly equal to the free spectral range $\omega_{FSR}$ of the resonator ($|\omega_M - \omega_{FSR}| \ll 1$) as well as $\omega_M = \omega_{mw}$.

The power of the light escaping the resonator and generating the base band signal can be presented as

$$\frac{P_{out}|_{BB}}{P_{in}} \simeq \sqrt{1 - \frac{\xi^2}{2} e^{i\phi_s} + \xi} \left( 1 - \frac{2\gamma}{\Gamma_A} \frac{\Gamma_+ \Gamma_-}{\Gamma_+ \Gamma_- + 2|g^2(t)|^2} \right) + \frac{2\gamma^2}{\Gamma_A} \frac{|g^2(t)||\Gamma_+|^2 + |\Gamma_-|^2}{|\Gamma_+ \Gamma_- + 2|g^2(t)|^2} \right)$$  

(1)

where the first and the second terms in the right hand side of Eq. (1) stand for the relative power at the carrier frequency and at the sideband frequencies (here we take into account the first sideband pair only), $\Gamma_A = \gamma + \gamma_c + i(|\omega_0 - \omega|)$ and $\Gamma_\pm = \gamma + \gamma_c + i(|\omega_0 - \omega|) \pm i(\omega_{FSR} - \omega_M)$ are the tuning parameters for the carrier and sideband modes, $\omega_0$ is the frequency of the pumped WGM, $\gamma$ is the frequency of the laser, $\gamma_c$ are the intrinsic and coupling half widths at half maximum of the WGM resonances ($\gamma + \gamma_c$ is the loaded half width at half maximum), $\xi$ is the phase mismatch parameter for the coupling prism and the resonator, $\phi_s$ is the phase of the part optical signal that does not interact with the resonator, and $g(t)$ is the modulation parameter given by

$$g^2(t) = \omega^2 r_{33}^2 n_e^4 \eta^2 \frac{\pi Q_M}{n_M^2 \omega_M} \left( P_{mw} + P_{LO} + 2 \sqrt{P_{LO} P_{mw}} \cos(\omega_M - \omega_{LO} + \phi_M) \right).$$  

(2)

Here, $Q_M$ is the quality factor of the critically loaded microwave mode, $r_{33}$ is the electro-optical coefficient of the resonator host material, $n_e$ and $n_M$ are the indexes of refraction of the material, $\gamma_M$ is the volume of the microwave field, $\eta = (1/V_c) \int |\Psi_e|^2 |\Psi_M|^2 dV < 1$ is the overlap integral of the optical and microwave fields, $|\Psi_e|^2$ and $|\Psi_M|^2$ are the spatial distributions of the power of the optical and microwave fields respectively, $(1/V_c) \int |\Psi_e|^2 dV = 1$, $P_{mw}$ is the power of the microwave signal, $P_{LO}$ is the power of the local oscillator, $\phi_M$ is the relative phase of the local oscillator and the signal.

In the case of the resonant tuning of the laser as well as quasi-critical ($\gamma_c = \gamma$ but $\xi$ is not necessary equal to 1) coupling the unsaturated signal is given by

$$\frac{P_{out}|_{BB}}{P_{in}} \simeq \frac{\xi^2}{2} \frac{2g^2(t)}{4\gamma^2 + (\omega_{FSR} - \omega_M)^2}.$$  

(3)

Therefore, the microwave bandwidth of the receiver is equal to $4\gamma$, which corresponds to the optical bandwidth.

It is convenient to introduce the microwave saturation power $P_{sat}$ of the receiver showing when the response of the receiver starts to decrease with the increase of the signal power

$$P_{sat} = \frac{n_M^2 \omega_M \gamma_M}{8\pi \eta^2 Q_M r_{33}^2 n_e^2}.$$  

(4)

It corresponds to $\Gamma_+ \Gamma_- = 2g^2(t)|_{\text{max}}$ and allows to estimate the maximum detectable microwave power which should not to exceed significantly the saturation power in avoidance.
of the decrease of the signal. The receiver is also characterized with the gain $G$, which is given by the ratio of the power of the output intermediate frequency (IF) signal and the input high frequency signal. We assume that the DC part of the photocurrent generated by the modulated light on the slow photodiode is filtered out. The AC part of the photocurrent ($j = \mathcal{R}P_{\text{out}}|_{\text{BB}}$) is

$$j_{\text{AC}} = 2\mathcal{R}^2 \frac{P_{\text{in}}}{P_{\text{sat}}} \frac{P_{\text{LO}} P_{\text{mw}} \cos[(\omega_M - \omega_{\text{LO}})t + \phi_M]}{1 + (\omega_{\text{FSR}} - \Omega_M)^2 / (4\gamma^2)},$$

(5)

where $\mathcal{R}$ is the responsivity of the photodiode. The average power of the AC signal is given by expression

$$P_{\text{AC}} = \frac{4 \rho_{\text{pd}} \mathcal{R}^2 P_{\text{in}}^2}{P_{\text{sat}}^2} P_{\text{LO}} P_{\text{mw}} \left[1 + \frac{(\omega_{\text{FSR}} - \Omega_M)^2}{4\gamma^2}\right]^{-2},$$

(6)

where $\rho_{\text{pd}}$ is the resistivity of the photodiode. The gain of the receiver is

$$G \equiv \frac{P_{\text{AC}}}{P_{\text{mw}}} = \frac{4 \rho_{\text{pd}} \mathcal{R}^2 P_{\text{in}}^2}{P_{\text{sat}}^2} P_{\text{LO}} P_{\text{mw}} \left[1 + \frac{(\omega_{\text{FSR}} - \Omega_M)^2}{4\gamma^2}\right]^{-2}. \tag{7}$$

The output noise power of the receiver is given by the thermal (input and the intrinsic noises) and relative intensity noises

$$P_{\text{noise}} = \left[(1 + G)k_B T + \rho_{\text{pd}} \mathcal{R}^2 P_{\text{DC}} \frac{\text{RIN}}{\xi} \right] \Delta F,$$

(8)

$k_B$ is the Boltzmann constant, $T$ is the temperature, $\xi < 1$ is the quantum efficiency of the photodiode, $\Delta F$ is the video-bandwidth, and $P_{\text{DC}}$ is the DC part of the optical power falling on the photodiode. The minimum of the RIN is given by $\text{RIN}_{\text{min}} = 2h\omega / P_{\text{DC}}$. In a realistic receiver $P_{\text{DC}} \simeq (1 - \xi^2)P_0$, and the noise power is primarily given by the RIN. In an ideal receiver $\xi \to 1$, $G \gg 1$, and the thermal noise determines the input RF noise power.

The noise floor power of the ideal receiver, determined as the power that corresponds to unity signal to noise ratio ($S/N = 1$) is

$$P_{\text{mw noise floor}} = \frac{P_{\text{noise}}}{G} \tag{9}$$

The noise floor power and the saturation power determine the dynamic range of the receiver

$$DR \approx \frac{P_{\text{sat}}}{P_{\text{mw noise floor}}} \tag{10}$$

In the ideal case $DR = P_{\text{sat}} / (k_B T \Delta F)$. The dynamic range does not depend on either the optical power or the saturation power of the receiver and is given by

$$DR \leq \frac{\xi^4}{(1 - \xi^2)^2} \frac{\xi}{\text{RIN} \Delta F} \tag{11}$$

when the noise of the receiver is determined by the RIN of the laser, the signal frequency coincides with the FSR of the resonator, and $P_{\text{LO}} = P_{\text{sat}}$. Low frequency RIN can reach $-130 \text{ dB/Hz}$ for 3 mW output optical power for a standard DFB laser. Assuming that $\Delta F = 5 \text{ MHz}$, $\xi^2 = 0.6$, $\xi = 0.8$, we obtain $DR \leq 66 \text{ dB}$. On the other hand, the dynamic range of the ideal receiver having $P_{\text{sat}} = 10 \mu\text{W}$ is $DR = 87 \text{ dB}$. For a good DFB laser RIN can be as low as $-160 \text{ dB/Hz}$, so the noise of such a laser is given by thermal noise, not by the RIN. Increasing the saturation
power leads to increase of the dynamic range of the receiver. The receiver with $P_{\text{sat}} = 1 \text{ mW}$ can have 107 dB dynamic range.

In detection of deterministic narrowband signals where optimal filtration or postfiltration can be applied the effective noise bandwidth of the receiver can be reduced several orders of magnitude. Such a reduction will lead to a significant increase of the dynamic range as well as the sensitivity of the receiver.

Let us theoretically estimate the parameters of the experimental realization of the coherent receiver reported above. We assume that $Q = 4 \times 10^7$, so that FWHM of the optical resonance is 5 MHz, $\Delta F = 5 \text{ MHz}$, and $\gamma = \gamma_c = 2\pi \times 1.3 \times 10^8 \text{ s}^{-1}$. We further assume $Q_M = 60$, $\omega_M = 2\pi \times 35 \text{ GHz}$, $P_{\text{in}} = 50 \mu \text{ W}$, $r_{33} = 30 \text{ pm V}^{-1} \text{ esu}$, $n_e = 2.1$, $n_M = 5.4$, $\gamma_M = 3 \times 10^{-6} \text{ cm}^3$, $P_{\text{pd sat}} = 10 \mu \text{ W}$, $P_{\text{microwave noise floor}} = 3 \text{ pW}$, and $\text{DR} = 65 \text{ dB}$. In the experiment reported in Fig. 12 we have lower gain because of the optical and microwave losses throughout the system.

### 4. Discussion

To improve the sensitivity as well as dynamic range of the receiver we need to increase the optical power retrieved out of the resonator as well as to reduce the laser noise. Locking of the laser to the resonator is very promising because it results in a decrease of both low frequency RIN and phase noise of the laser [13]. Moreover, locking allows keeping the laser frequency exactly at the center of the WGM, so the transformation of the phase to amplitude laser noise is significantly suppressed. The locking can be realized, e.g., using Rayleigh scattering [14].

In our experiment we were unable to increase the optical power beyond 50 $\mu \text{ W}$ because of the optical damage of lithium niobate as well as mode interactions in the resonator [15]. We have found that the optical damage is much lower in lithium tantalate resonators. The power can also be increased if one reduces the quality factor of the resonator. Such a reduction leads to the larger bandwidth of the receiver on the one hand, and lower saturation power on the other. Usage of single-mode resonators [16] will also lead to a significant reduction of the mode interaction because of the elimination of the unwanted modes.

Let us now compare the coherent and quadratic [7, 8, 12] receivers. According to the results of the experiments reported in [12] and this paper, we find that the dynamic range of the coherent receiver is at least 10 dB larger than the dynamic range of the quadratic receiver. According to our theoretical calculations the dynamic range of the coherent receiver is 20 dB higher for the same experimental conditions and can potentially be 40 dB higher for 1 mW optical pump power. The sensitivity of the coherent receiver is also much higher than the sensitivity of the quadratic receiver. Moreover, the coherent receiver allows measuring the phase and frequency of the microwave signal, along with its amplitude.

Resonant quadratic photonic receivers [7, 8, 12] are fundamentally nonlinear. A major problem with them is the generation of second-order products of signals from two nearby RF channels. One component of these second-order products is located at base band, and thus interferes with the desired signal, degrading performance. The coherent receiver we discuss here is linear due to presence of the strong LO. It can be used for reception of several signals coming from a single channel.

The performance of the linear receivers is generally given by the sensitivity, spurious-free dynamic range, and third-order intercept point. Spurious-free dynamic range and third-order intercept point depend on the residual cubic nonlinearity of the receiver. The method for characterizing a linear receiver is based on injection of equal levels of two closely spaced carriers into the device and the study of generated spurious sidebands at product frequencies. Our coherent photonic receiver does not possess a significant cubic nonlinearity, and the nonlinearity of the photodiode as well as the RF circuitry can be quite small. Thus, determinations of a
third order intercept point as a measure of signal distortion is not applicable for the device. Stated more succinctly, our photonic receiver does not produce any distortion resulting from third order nonlinearity by itself.

On the other hand, the receiver does produce distortion as a result of the second order nonlinearity. But as is well known, all distortions resulting from the second order nonlinearity occur at frequencies that are widely separated from the input frequency. Consequently there are no distortion of the closely separated signals. For example, if the receiver has 35 GHz LO and two signals with carrier frequencies 35.001 GHz and 35.0011 GHz fed into the RF resonator, the receiver shifts frequencies of those signals to 1 MHz and 1.1 MHz in the base band. The second order nonlinearity results in the spurious sideband at 100 kHz frequency. This low frequency sideband can be easily filtered out. As the rule, if the LO frequency is separated with the receiver band by several reception bandwidths, the second order nonlinearity does not degrade the receiver performance. If the LO frequency located within the reception band, the second order nonlinearity limits the spurious free dynamic range of the receiver to approximately 50 dB.

5. Conclusion

We have demonstrated experimentally and studied theoretically an all-resonant coherent photonic microwave receiver based on a lithium niobate whispering gallery mode resonator. The receiver has high sensitivity and large dynamic range, and its performance does not degrade for higher microwave frequencies. Hence, the photonic receiver is an attractive alternative to the conventional electronic receivers and will likely enable new applications.