Photonic Front-end for Millimeter Wave Applications

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***Abstract*—We propose theoretically and demonstrate experimentally both a direct (quadratic) and a coherent millimeter wave photonic receivers operating at 35 GHz carrier frequency. These devices are made based on lithium niobate or lithium tantalite or quartz optical whispering gallery mode resonators coupled to a millimeter wave signal with a strip line. The quadratic receiver has sensitivity exceeding -70 dBm in a 3 MHz frequency band. It also has more than 40 dB of dynamic range. The coherent receiver can have a dynamic range in excess of 100 dB in a 5 MHz band, as well as a much higher sensitivity. The coherent operation of the receiver is achieved using a millimeter wave local oscillator fed into the strip line resonator along with the millimeter wave signal. We also discuss possible photonic methods for the generation of spectrally pure local oscillator signals suitable for the application in the coherent receiver.**

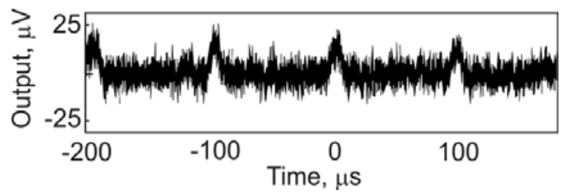
I. Introduction

DIRECT processing of high frequency millimeter wave signals with conventional electronic approaches is hindered by the absence of efficient amplifiers and detectors. Photonic receivers translate the millimeter signals to the baseband, where subsequent efficient detection is feasible. Examples of such receivers based on all-resonant interaction of light and RF signals in solid-state whispering gallery mode (WGM) resonators have been recently demonstrated [1-5]. The sensitivity of the photonic receivers based on these resonance structures can be very high in the relatively narrow reception bandwidth. However, unlike conventional receivers, the sensitivity of the photonic devices does not degrade with increasing frequency. These devices are compact and have low power consumption. X- and K_u-band WGM-based receivers have been demonstrated previously [1-5]. Here we present results of our experimental as well as theoretical study of the direct and phase sensitive (coherent) WGM-based millimeter wave photonic receivers operating in the K_a-band. This work can be readily extended for realization of higher frequency systems operating at W-band and beyond.

II. Results

We have demonstrated a quadratic receiver that downconverts K_a-band millimeter wave pulses directly into base-band [6]. A high Q lithium niobate WGM resonator was excited with 1319 nm laser light at the resonant frequency of one of the TE modes. When a signal pulse modulation with repetition frequency 10 kHz to 100 kHz impressed on the 35 GHz carrier was applied to the resonator, the light output detected at a low frequency photodiode directly reproduced the envelope of the RF pulses. This direct signal recovery did not require a LO, and is the result of the nonlinear response of the material of the WGM resonator modulator, combined with the automatic filtering produced by the low-pass response function of the photodiode. Receiver baseband response with 1.4 nW pulses at 35 GHz applied to the WGM resonator was 3 dB above the tangential noise floor, implying a sensitivity of 0.1 nW for SNR = 1 (Fig. 1).

Fig. 1 Receiver response with 1.4 nW pulses at 35 GHz



applied to the WGM resonator. Response shown is ~3 dB above tangential implying a sensitivity of ~0.1 nW for SNR = 1. The optical signal was demodulated on a slow photodiode to obtain the baseband response.

The receiver has the best sensitivity when light is in resonance with the WGM. To study the dependence of the sensitivity of the receiver on the frequency of light we sent a train of RF pulses into the receiver and tuned the frequency of light through the optical resonance. The result of the measurement is shown in Fig. 2.

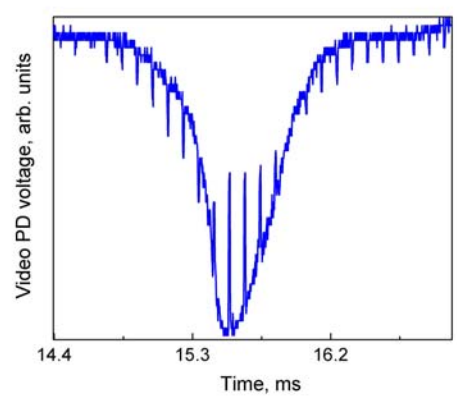


Fig. 2 Receiver response with 15 μW pulses at 35 GHz applied to the WGM resonator. The frequency of the laser is slowly scanned through the TE WGM having approximately 3 MHz loaded linewidth. The transmission of the nearly resonant light increase, while the transmission of the off-resonant light decreases when the RF pulse is applied. The receiver is nearly saturated at the given RF power.

In a second study we have demonstrated a coherent K_a band millimeter wave photonic receiver [7]. In this experiment a lithium niobate WGM resonator with 35 GHz free spectral

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range was excited using 1550 nm laser light at the resonant frequency of one of the optical TE modes. The laser frequency was kept at the center of the optical resonance using the injection locking technique. The light output of the resonator received at a low frequency photodetector reproduced the product of the millimeter wave signal and the LO, both applied to the resonator. We used 10 kHz to 100 kHz signals modulated on the 35 GHz carrier as well as a DC LO detuned 50 kHz to 500 kHz from the signal carrier frequency. The sensitivity of the receiver corresponding to SNR=1 was better than 0.1 nW, and the dynamic range was more than 50 dB (Fig.3).

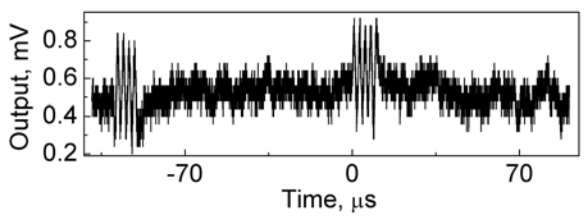

Fig. 3 The coherent receiver response. The optical coupling efficiency is approximately 60%, and the optical insertion loss away of the WGM resonance is less than 3 dB. The input optical power of the receiver does not exceed 50 μW. The signal pulses have 0.4 nW power and 20μs duration. Their carrier frequency is approximately 35 GHz (FSR of the WGM resonator). Microwave local oscillator (LO) has 10μW DC power and 400 kHz detuning from the signal carrier frequency. There is no time averaging of the response. The fringes occur due to the 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 linewidth of the WGMs and is approximately 5MHz. 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 detector resistance ρ =10 kOhm and amplitude of the retrieved signal V=0.35 mV. The power of the measured noise approximately corresponds to the thermal noise power in the bandwidth of the measurement.

The receivers have almost two orders of magnitude improved performance as compared with electronic receivers [6], and are more than three orders of magnitude more sensitive compared with earlier demonstrations of similar photonic devices operating at lower frequencies [4,5]. Since our lithium niobate WGM based modulator can be fabricated to operate at higher frequencies, and since the detector used is a baseband photodetector, the scheme can be used for frequencies in the W-band and higher. Furthermore, the photonic receiver front end described here can be packaged in a small size, about 1 cubic centimeter, and can thus be attractive for applications where size, weight and power are important. These photonic receivers are compelling alternatives to the conventional electronic receivers and will likely enable new applications.

To improve the sensitivity and the 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. Injection 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. 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. Injection locking can be realized, e.g., using Rayleigh scattering.

Let us now compare the coherent with the quadratic receiver. We have found 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 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 baseband, and thus interferes with the desired signal, degrading performance. The coherent receiver we discuss here is linear due to the presence of the LO. It can be used for reception of several signals coming from a single channel. The coherent photonic receiver does not possess a significant cubic nonlinearity, and the nonlinearity of the photodiode and 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.

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