Towards microwave photon counting via frequency up-conversion

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***Abstract*—We have demonstrated nonlinear optical up-conversion of 100 GHz signal into optical range using high-Q whispering gallery mode (WGM) resonators with quadratic nonlinearity. This approach has allowed us to achieve the record power conversion efficiency of 0.5% with as low as 16 mW of CW optical pump power. We furthermore show that by implementing the WGM resonator for the microwave as well as for the optical modes, the unity photon-number conversion efficiency can be in principle achieved. Combining such a converter with a state-of-the-art optical photon counter it will be possible to count the microwave photons whose frequency is as low as 0.1 THz, at room temperature.**

I. Introduction And Background

Counting individual photons is the natural sensitivity limit for a detector of electromagnetic radiation. While readily achieved in the optical domain, this limit remains challenging in the THz and sub-THz electromagnetic frequency range.

The nature of these difficulties becomes obvious if we introduce the photon counting criterion requiring that the photon energy $\hbar\omega$ should exceed the noise-equivalent signal power (NEP) times the detector's response time τ. In the optimal case this definition leads us to

$$kT \cdot \Delta\omega \cdot \tau < \hbar\omega \cdot \eta\,, \qquad (1)$$

where $\Delta\omega$ is the detector bandwidth and η is its quantum efficiency. If $\Delta\omega\tau = 2\pi$, then criterion (1) for a perfect ($\eta = 1$) detector simply says that the photon energy must exceed the photon counter temperature. For the sub-THz frequencies, this means very low temperatures. In practice, the detector's response time is much slower than its inverse bandwidth, which makes the low temperature requirement far more stringent. For example, counting of 2 THz photons was demonstrated using a quantum dot at 0.3 K [1]. The possibility of detecting 1 THz photons with superconductive nanobolometers at below 0.2 K has been also discussed [2].

Nonlinear frequency conversion of THz photons into optical domain is another approach that has been previously used for the infrared and THz signal detection, e.g. [3,4]. In this case the microwave converter bandwidth $\Delta\omega$ and optical photon counter response time τ are determined by different physical processes and need not be bound by the time-frequency uncertainty. It is possible to have $\Delta\omega\tau << 1$, which would give this approach a significant advantage in the sense of low temperature requirements. However the practical usefulness of the converter-detector technique is limited by low conversion efficiency. In the most successful approach known to us [4], the peak power conversion efficiency was approximately 0.06% [5] in the 0.5-0.7 THz range. The NEP density of the measurement reported in [4] can be estimated as 34 pW/Hz. Substituting this instead of kT in (1), we find that this experiment cannot satisfy the photon-counting criterion for any reasonable bandwidth $\Delta\omega$.

The situation improves greatly if the frequency upconversion takes place in a high-Q whispering gallery mode (WGM) resonator. Previously, we have theoretically shown [6] that the WGM-based up-converters can achieve unity conversion efficiency in continuous regime. In this case it is easy to show that the photon-counting criterion can be satisfied at room temperature for photon frequencies as low as 120 GHz, assuming the state-of-the-art $\tau = 5$ ns.

The WGM-based up-converter utilizes three propagating WGMs: the optical pump mode, the sub-THz mode populated by the microwave signal, and the optical anti-Stokes mode, which becomes excited if the following phase-matching conditions are satisfied:

$$\omega_{RF} = L_{RF}\Omega, \text{ and } L_{RF} = L_{AS} - L_P\,, \qquad (2)$$

where L_{RF}, L_{AS} and L_P are the orbital momenta of the THz, anti-Stokes and pump WGMs, respectively, and Ω is the optical free spectral range (FSR) of the resonator. Conditions (2) are easily satisfied taking advantage of the strong waveguide dispersion of the THz mode [6].

II. Results

We first demonstrated the efficient nonlinear coupling of optical WGMs to sub-THz radiation. A schematic drawing of this experiment is shown in Fig.1.

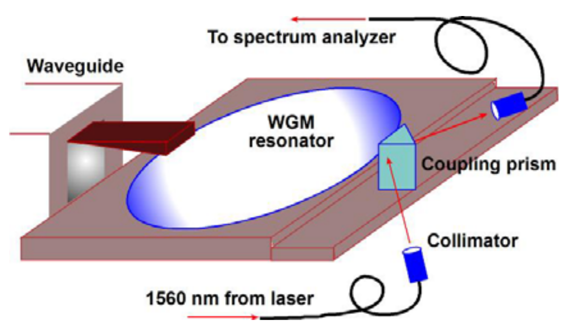

Figure1: Schematic of the nonlinear coupling experiment.

A WGM resonator disk made from a z-cut lithium niobate wafer has the radius 1.8 mm and thickness 0.22 mm. The diamond prism couples the laser light of the wavelength λ = 1560 nm in and out of a WGM with $Q = 10^7$. The coupling efficiency was greater than 99%. The optical sidebands shown in Fig.2 were observed at RF frequency of 101.38 GHz, which is equal to eight times the optical FSR $\Omega = 2\pi \cdot 12.64$ GHz.

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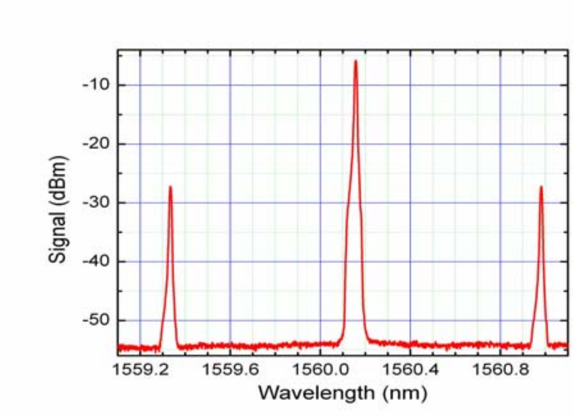

Figure2: The spectrum of the optical output in presence of a 0.4 mW microwave signal. The optical power at the coupling prism input is 16 mW.

In this experiment the power conversion efficiency of the microwaves to *each* Stokes and Anti-Stokes optical sidebands was approximately 0.5%, which corresponds to the photon-number conversion efficiency of $2.6\cdot 10^{-6}$, via the Manley-Rowe relation. The NEP density was 1.6 fW/Hz. Achieving the photon counting regime with these parameters would still require the unrealistic conversion bandwidth of about 1.3 Hz, while the actual bandwidth (i.e., the width of the optical WGM) was approximately 20 MHz. Notice however that the demonstrated NEP density exceeds the theoretical limit from [6] $2kT\approx 8\cdot 10^{-21}$ W/Hz by approximately the same amount unity exceeds the demonstrated photon-number conversion efficiency. This factor is also close to the factor we are "short of" to approach the photon counting regime at room temperature. Therefore the next step is to achieve the (nearly) unity photon-number conversion efficiency, which should be possible [6] in the system with three-mode interaction.

The experimental setup for studying the microwave WGMs in a lithium niobate ring is shown in Fig. 3. The ring is placed on a fused silica post whose dielectric constant is lower than that of lithium niobate. In this configuration the microwave field is concentrated mainly inside of the lithium niobate ring, which provides good coupling with the external waveguide as well as good overlap with the optical field. The conversion will be efficient as long as the nonlinear coupling rate exceeds the loss rate in the microwave WGM. The ring height is 0.29 mm, inner radius 2.48 mm, outer radius 2.9 mm.

The microwaves are supplied by a fused silica waveguide, which is coupled to the resonator through the evanescent field. For the efficient coupling, the phase velocities in the waveguide and in the resonator should match, which is achieved by tapering the waveguide. Translating the taper along its axis we found the optimal coupling position, and obtained the microwave spectrum shown in Fig. 4. From the spectrum in Fig. 4 we see that the signal coupling from the THz waveguide into the resonator as high as 82\% was readily achieved. We also determine the microwave WGM quality factor of Q = 100.

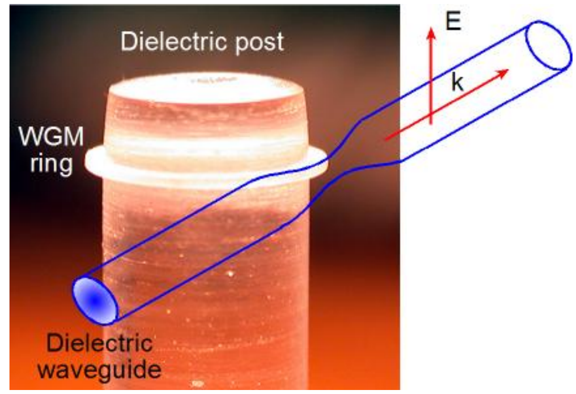

Figure3: A lithium niobate WGM ring resonator mounted on a fused silica post, coupled with a tapered dielectric waveguide.

The thin ring in this experiment acts as a looped single mode microwave waveguide. The mode sequence in Fig. 4 is indexed by the orbital number L_{RF}. Once this number is determined, one can solve the set (2) and implement the sub-THz photon counting using our technique.

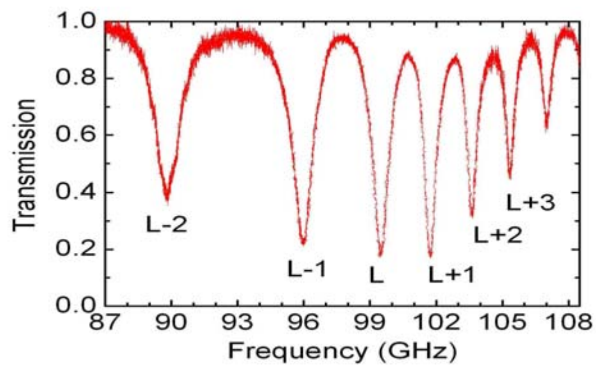

Figure4: Microwave spectrum of the ring WGM resonator shown in Fig. 3.

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