Efficient upconversion of sub-THz radiation in a high-Q whispering gallery resonator

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We demonstrate efficient upconversion of sub-THz radiation into the optical domain in a high-Q whispering gallery mode resonator with quadratic optical nonlinearity. The $5 \cdot 10^{-3}$ power conversion efficiency of continuous wave 100 GHz signal is achieved with only 16 mW of optical pump.

Detection of weak sub-THz signals, and ultimately counting of photons, is desirable for quantum communications, astronomy, and spectroscopy applications. Photomultipliers are now determined by different physical processes and is independent of the detector frequency range $\Delta \omega$. Typically $\tau \Delta \omega \gg 1$, which is one reason why they have to operate at temperatures much lower than a single-photon energy ($1\text{THz} \approx 48 \text{K}$). Other reasons have to do with the detector properties, such as the $T_e$ of the superconductors. Naturally, it is desirable to create sub-THz photon counters operating at room temperature. A nonlinear conversion of low frequency photons into optical domain is useful here. This approach should allow for $\tau \Delta \omega \ll 1$, because the photon-counting detector response time $\tau$ and the conversion frequency range $\Delta \omega$ are now determined by different physical processes.

Sub-THz photon counting based on nonlinear conversion has not been realized yet. The main limitation here is low conversion efficiency. The best known to us peak efficiency of power conversion of approximately $6 \cdot 10^{-4}$ was demonstrated in the 0.5-0.7 THz range with pulsed optical pump of 500 W peak and one watt average power. Therefore the CW power conversion efficiency was $1.2 \cdot 10^{-6}$, which corresponds to the photon-number conversion efficiency of $3.7 \cdot 10^{-9}$ as can be found from the Manley-Rowe relation.

We report on a three orders of magnitude improvement in the conversion efficiency, using a high-Q optical whispering gallery mode (WGM) resonator. WGM resonators have already been successfully used in nonlinear optics in general and in the microwave photonics in particular. Our achievement is in using this technique for efficient conversion of 100 GHz radiation.

Our setup is shown in Fig. 1. The WGM resonator disk made from a z-cut lithium niobate wafer has 1.8 mm radius and 0.22 mm thickness. It is mounted on a brass support (not shown in Fig. 1) attached to the opening of a metal waveguide supplying the microwave signal. A brass wedge inserted into the waveguide opening is used to optimize the signal field coupling into the disk. Both microwave and optical fields are polarized along the z-axis, as shown in the Figure, so that the largest nonlinearity component $r_{33}$ is employed.

![FIG. 1: Schematic of the experiment setup. The WGM resonator is coupled to the input and output free-space optical beams by a diamond prism, and RF-coupled to the signal field supplied by the waveguide. On the inset: a photograph of interference fringes arising between the rim of the resonator disk and a flat surface.](image-url)

The pump light of the wavelength $\lambda = 1560 \text{ nm}$ is coupled to the resonator using frustrated total internal reflection in a diamond prism. The coupling is adjusted...
by a few degree temperature variation of the thoroughly thermo-stabilized brass support. This changes the gap between the resonator and the prism, due to the differential thermal expansion of the materials. Sub-degree variations of the temperature are used to tune the WGMs frequencies, due to thermal expansion of the disk.

When the incident light reflects from the back side of the prism, its evanescent field propagates outside along the prism surface with the wave vector projection \( \vec{k}_l = n_\text{d}(\omega/c)\sin \theta \), where \( n_\text{d} \) is the refraction index of diamond and \( \theta \) is the incidence angle. The wave vectors of light inside and outside of the disk should match, which yields the following condition for the incidence angle:

\[
\sin \theta = \frac{n_e}{n_\text{d}}.
\]

In [3], \( n_e \) is the extraordinary refraction index of lithium niobate. To establish the second condition of efficient coupling, we visualize the coupling region as the first-order Newton “ring” arising between the resonator disk rim and a flat surface, see the inset of Fig. 1. The ratio of the ellipse axes is equal to the square root of the ratio of the two local curvature radii \( R \) (the disk radius) and \( r \) of the rim. It is congruent with the incident beam “footprint” if

\[
r/R = (\cos \theta)^2.
\]

Given \( \theta \), condition (3) yields the optimal \( r/R \) ratio.

A WGM resonance can be observed as absorption of the light transmitted from the laser source to the spectrum analyzer (see Fig. 1). In our experiment the contrast of the resonance reached 99.96%, see Fig. 2. Notice that the baseline in Fig. 2 is below the unity. This 4 dB broadband loss originates from the reflections of two diamond surfaces, the fiber tips and collimation lenses, as well as from the possible mismatch of the collection optics. The latter suggests that the observed high contrast could be partially contributed to by some interference phenomena, e.g., the fringes in the output light beam. Although we made an effort to minimize these effects by a thorough alignment procedure, an additional study of the WGM resonators coupling is required.

First we observed the optical WGM spectrum of our resonator by sweeping the laser frequency, and measured the free spectral range (FSR) \( \Omega = 2\pi \cdot 12.64 \text{ GHz} \) and \( \Delta \omega \approx 2\pi \cdot 20 \text{ MHz} \), which yields the quality factor \( Q \approx 10^7 \). Then we set the laser at one of the WGMs and varied the signal frequency around \( \omega_{\text{rf}} = 8\Omega \approx 2\pi \cdot 101.12 \text{ GHz} \). The sidebands were observed at 101.38 GHz (see Fig. 3). It is interesting to point out that in this case both Stokes and anti-Stokes sidebands have equal amplitudes; if however we change the signal frequency we can have one sideband exceed the other or vice versa, depending on the sign of the detuning. This can be considered as an evidence of significant WGM frequency dispersion on the span of 16 FSRs.

The employed method of microwave coupling into the disk is rather inefficient, since the main part of the microwave energy likely reflects back into the waveguide or scatters into space. However the CW power conversion efficiency into each Stokes and anti-Stokes sideband was found to be \( 5 \cdot 10^{-3} \), which corresponds to a photon-number conversion efficiency of \( 2.6 \cdot 10^{-6} \) into each sideband, and \( 5.2 \cdot 10^{-6} \) into both bands. This greatly improves the results of [11].

To estimate how closely our experiment comes to the photon counting limit (2) we find the experimental value of the NEP density \( S(\omega) \) and substitute into (2), finding the maximum detection bandwidth \( \Delta \omega_{\text{max}} \) allowing for photon counting. The resolution bandwidth of the optical spectrum analyzer was 1.23 GHz. Each Stokes and anti-Stokes signal observed within this bandwidth was some 27 dB above the instrumental noise floor (see Fig. 2), while the input microwave power was 0.4 mW. Therefore the NEP density can be found as the power-to-bandwidth ratio less 27 dB, which yields \( S(\omega) = 1.6 \).
fW/Hz and $\Delta \omega_{\text{max}} = 1.3$ Hz. Notice that if we increase the conversion efficiency to unity, this bandwidth will increase to 0.52 MHz, which would require $Q \approx 4 \times 10^8$. This quality factor value is certainly within reach [17].

A unity conversion efficiency in continuous regime is theoretically predicted [3] for the all-resonant upconverters, supporting the microwave WGM as well as the optical ones. The interacting modes have to satisfy the phase-matching conditions $\omega_{rf} = L_{rf}\Omega$ and $L_{rf} = L_{a} - L_{p}$, where $L_{rf}, L_{a}$ and $L_{p}$ are the orbital momenta of the THz, anti-Stokes and pump WGMs, respectively, and $\Omega$ is the optical FSR of the resonator. These conditions can be satisfied by taking advantage of the strong waveguide dispersion of the sub-THz mode.

Unity conversion efficiency can be achieved when the loss rate of the sub-THz mode $\gamma = \gamma_{nl} + \gamma_{abs}$ is dominated by the rate of nonlinear frequency conversion: $\gamma_{nl} \gg \gamma_{abs}$. Furthermore, the optical WGMs need to be strongly coupled to the free space, so that for the optical loss rates $\Gamma > \Gamma_{abs}$ would hold. The detection bandwidth $\Delta \omega$ is then equal to that of the loaded optical WGM.

The theoretical value found in [3] for the NEP spectral density is $S = 2k_{B}T$, for a resonator which is in thermal equilibrium with the surrounding heat bath. If the resonator is decoupled from the bath, its own thermal fluctuations contribution to the microwave noise is suppressed by virtue of the fluctuation-dissipation theorem. Then instead of $T$ one should use $T_{eff} = TT_{abs}/\Gamma < T$, which can bring the noise level below the classical limit.

For a conservative estimate we assume that the resonator is coupled with a thermal bath at $T = 300$ K. We further assume $Q = 10^8$ [17], $\lambda = 1560$ nm (so that $\Delta \omega \approx 2\pi \cdot 2$ MHz), and $\tau = 5$ ns. Then from the photon counting criterion [2] we find $\omega > 2\pi \cdot 0.12$ THz, which means that counting 0.12 THz photons should be possible. If we decouple the resonator from the thermal bath it should be possible to count photons at even lower frequencies, and to reach higher sensitivity.

To summarize, we have demonstrated nonlinear conversion of sub-THz radiation to optics with efficiency greatly surpassing the state of the art. The NEP density in our measurement was a factor of $5 \cdot 10^{-6}$ worse than the theoretical limit $2k_{B}T = 8 \cdot 10^{-21}$ W/Hz for an all-resonant WGM converter with unity efficiency [3]. This factor is very close to the two-band photon-number conversion efficiency $5.2 \cdot 10^{-6}$ we have measured, which means that the deficiency of our experiment is solely due to insufficient conversion efficiency. We believe that realization of this method with an all-resonant WGM converter has a potential for achieving sub-THz photon counting at room temperature. Benefits from its practical implementation are expected in the areas of quantum information and computing (especially based on quantum electronic circuits), astronomy, and spectroscopy.

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