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Room temperature radiometer based on an up conversion process for CubeSats applications

Luis Enrique Garcia Munoz*[a], Gabriel Santamaria Botello[a], Kerlos Abdalmalak[a], Michal Wasiak[a]
[a] Universidad Carlos III de Madrid, Avenida Universidad, 30, 28911, Leganes, Madrid, Spain

ABSTRACT

Radiometry in the sub-millimeter and THz region is required for applications as imaging, spectroscopy, earth observation, planetary missions and radio astronomy. The recent advances in the development of high electron mobility transistors (HEMT) low noise amplifiers (LNAs) have pushed their operation frequency to the sub millimeter range, showing noise figures below 4dB inside cryocoolers. In the THz range detection has been achieved with Schottky mixers working either at room temperature or inside cryostats. They have shown noise temperatures comparable with those of the most recent LNAs. Superconducting devices such as SIS mixers can achieve near quantum limited noise performance while operating at 4K. Sensitive detection is also possible by adapting the principles of photonic detectors to THz frequencies. In this case, low noise operation implies cryogenic cooling of the detectors. Bolometer-based THz receivers operating in cryostats have shown photon counting sensitivity. In this work we study another approach proposed in the last two decades for high sensitivity THz detection at room temperature. The detection principle consists on taking advantage of the nonlinearity of crystals such as lithium niobate to enable a sum frequency generation (SFG) process that boosts the THz photon energy to the optical domain. This occurs via electro-optic modulation of the laser pump by the THz radiation when the waves are phase-matched inside the crystal. To significantly increase the conversion efficiency, an ultra high-Q whispering-gallery resonator (WGR) is used to confine and enhance the optical field. The WGR is also resonant in the THz domain, enhancing further the photon conversion efficiency. In this work we present optimized geometries for the doubly resonant WGR structure and coupling mechanisms. Then, theoretical models are used to predict the photon conversion efficiencies of such electro-optic modulators along with their thermal occupation levels and overall noise performance as THz radiometers.

Keywords: Radiometers, cubesat, THz, receivers.

1. INTRODUCTION

Detection of weak radiation at millimeter and sub-millimeter wavelengths is required for many applications of technological and scientific interest such as spectroscopy, imaging systems, earth observation and planetary missions, as well as radio astronomy. As there is a particular motivation for studying the cosmic microwave background, galaxies, stars and planetary systems at these wavelengths, future missions are currently being proposed and developed to retrieve unique information from this radiation [1–3]. Since the signals to be observed are usually weak compared to the thermal radiation generated by the receiver and its surroundings, ultra-low noise instrumentation is designed and placed inside cryostats to diminish the thermal noise contribution.

This dramatically increases the size, cost and complexity of instruments for airborne and space applications, while reducing the lifetime of the missions. In this paper we propose an alternative approach for designing flight-compatible receivers covering the mm-wave range that can eliminate or relax the cryogenic requirements: By passing the signal through a low absorption nonlinear crystal pumped by a laser, the microwave photons are up-converted to the optical domain where detectors are less susceptible to thermal noise at room temperature.

Unlike conventional detectors which are nearly perfect electromagnetic absorbers and thus ideal sources of thermal noise, the crystal is weakly coupled to the thermal bath by virtue of its low absorption and the low radiation losses of the mode. Hence, the microwave signal is up-converted to the optical domain before thermal noise populates the microwave mode. We show that with this novel paradigm, it is possible to realize a room temperature detector whose noise

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performance approaches the quantum limit. For this, besides the need of a high-Q microwave structure that guarantees the decoupling to the environment, a highly efficient up-conversion process is mandatory.

We experimentally demonstrate nonlinear up-conversion of 80GHz signals to a 194 THz carrier inside a high-Q lithium niobite whispering-gallery mode (WGM) resonator, showing two orders of magnitude higher efficiency than the best reported so far [4]. The paper is structured as follows: In Section 2 we discuss the WGM-based up-converter and analyze its thermal noise contribution and conversion efficiency. In Section 3, the performance of the proposed detector as a radiometer is estimated and compared with conventional technology

We follow an approach where background thermal noise cancellation is done at room temperature by cross-correlation in the optical domain. In Section 4, the experimental setup of a WGM-based up-converter is explained and results are shown. Finally, conclusions are given in Section 5.

2. ELECTRO-OPTIC UP-CONVERTER

In a conventional microwave receiver, noise originates from different sources with thermal noise being the dominant one due to the low energy of microwave photons. While microwave photons are completely masked by thermal noise if they are directly detected at room temperature, up-conversion into the optical domain boosts the photon energy, allowing for room temperature detection with commercially available devices.

It is challenging though to achieve a high photon conversion efficiency h, defined as the ratio of the numbers of output optical and input microwave photons. This is so because in optically transparent materials even the strongest second order susceptibilities c(2) are only on the order of a few pm/V. This leads to weak interactions unless extremely high field intensities are applied. Using a high-power optical pump entails a series of technical complications, such as e.g., excessive noise and a very strong pump suppression requirement.

These limitations have so far precluded any practical realization of the up-conversion approach. The field enhancement in high-Q whispering-gallery mode (WGM) resonators made of nonlinear crystals, helps to solve these problems, leading to the state-of-the-art efficiencies on the order of h $=10^{-7}$ per 1mW continuous wave (CW) pump power, for mm-wave signals [4, 5] (in the small signal regime, h scales proportionally with the pump power).

WGM cavities trap light by propagation along the resonator rim such that the light constructively interferes with itself to build up a resonance. Therefore, a microwave and an optical pump modes at frequencies n and np respectively, can be trapped in the same region of space, allowing for high modal overlap and strong nonlinear coupling via the second order response c(2) of the material's polarization. In general, this interaction generates multiple optical sidebands, but the resonator can be optimized to resonate only at the sideband produced by sum-frequency generation (SFG) and/or difference-frequency-generation (DFG) processes [6].

The SFG process is preferred since it is free of spontaneous parametric down conversion (SPDC) noise [7, 8]. Thus, an optical sideband at frequency ns = n + np is generated inside the resonator and then out-coupled and detected at room temperature with a photonic detector.

Since the SFG process is coherent and noiseless, the sideband contains all the information from the microwave signal provided that 100% of photons are up-converted. This scheme is depicted in Fig. 1 where a prism is used for in-coupling of the pump and out-coupling of the sideband. A dielectric rod waveguide is coupled to the antenna (for example, a horn) and to the resonator via the near evanescent field.

In a general nonlinear interaction scheme with undepleted pump and microwave modes (small signal regime), the photon-number up-conversion efficiency h scales linearly with the microwave and pump total power, and quadratically with the second order susceptibility c(2), the modal overlap and the interaction length [9]. In a WGM resonator, the power enhancement of optical and microwave modes (ratio between intra-cavity and input power), is proportional to the quotient between the corresponding quality factor and the resonator's radius. If the pump is monochromatic and critically-coupled, the conversion efficiency of a broadband microwave signal is given by [6, 10].

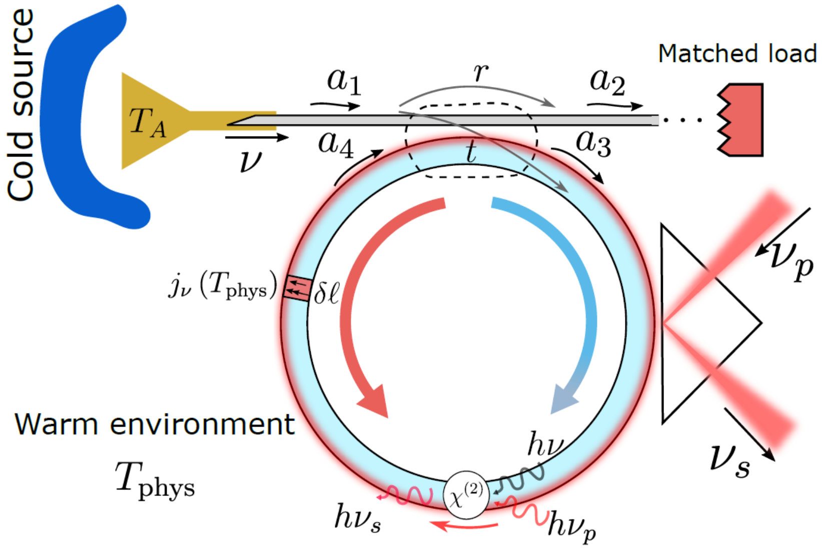

Figure 1. Coupling of mm-wave and optical radiation to the WGM resonator. The microwave coupling region (enclosed by the dashed curve) is considered small and lossless. Input and output modes in the waveguide and the resonator are defined with normalized field amplitudes ai(n) such that their squared norm equals to the power spectral density of the mode. The coupling system can be viewed as a 4-port network whose scattering matrix is characterized by the waveguide's reflection coefficient r = a2/a1 and waveguide-resonator transmission coefficient t = a3/a1. The cavity's reflection coefficient r0 = a3/a4 and cavity-waveguide transmission coefficient t0 = a2/a4 have the same magnitudes as r and t respectively, but different phase in general.

The key reason why we are interested in this type of solution is negligible thermal noise in the optical frequency range. It is due to significantly higher energy of the optical photons what makes them immune to relatively weak thermal noise of the receiver even at room temperature. To quantify the phenomenon, we use Planck function to express a ratio of the thermal noise power density to the photon energy [6]

$$\Theta_\nu(T) = \left(\exp(h\nu/k_B T) - 1\right)^{-1}$$

where h and k_B are Planck and Boltzmann constants respectively. At room temperature (300 K) the ratio is 14 orders of magnitude smaller for the optical domain at 193.54 THz than for microwaves at 200 GHz. The signal is upconverted before thermal noise populates, therefore the detector based on proposed scheme makes it possible to approach the quantum limit of sensitivity when operating at room temperature [7]. Moreover, the solution is easily scalable in frequency in contrast to semiconductor devises, thus operating in mm-wave and submm-wave ranges does not degrade performance of the radiometer.

The photon conversion efficiency depends on the resonator geometry and material properties, spacial distribution of WGMs in the resonator, couplings and the power of the pump. Moreover, there are two essential conditions to satisfy to achieve high conversion efficiency. The first is straightforward and represents energy conservation of the converter as a quantum-mechanical system

$$h\nu + h\nu_s + h\nu_p = 0$$

The second refers to the phase-matching that is related to spatial distribution of the modes and will be explained later in this section. Under assumption of critically coupled pump we can express photon conversion efficiency with [9, 13],

$$\eta = P_p Q_p Q_s \frac{g^2}{\pi h v_p^2 v_s}\left(\frac{Q_s}{Q_s^c}\right)\tau F$$

where P_p is the pump power, Q_p and Q_s are the loaded quality factors of the pump and sideband, respectively, Q_s^c is a coupling quality factor of the sidebands, τ describes roundtrip time in the resonator and F is a power enhancement of the microwave mode understood as the ratio of the intracavity power to the input power. A nonlinear coupling g describes the impact of spatial modes distribution on the conversion efficiency and is given by

$$g = \chi^{(2)}\zeta \frac{\int_V \mathbf{\Psi_p}\mathbf{\Psi}\mathbf{\Psi_s^*}\, dV}{\sqrt{\int_V |\mathbf{\Psi_p}|\, dV \int_V |\mathbf{\Psi}| dV \int_V |\mathbf{\Psi_s}|\, dV}}$$

where $\zeta = 4\pi\varepsilon_0\left(\frac{h}{8}\right)^{\frac{1}{2}}(v_p v_s v)^{\frac{1}{2}}/(\varepsilon_p\varepsilon_s\varepsilon)$ with ε_p, ε_s, ε being pump, sideband and microwave permitivities of the media, $\mathbf{\Psi_p}$, $\mathbf{\Psi}$, $\mathbf{\Psi_s}$ are vector eigenfunctions representing field distributions of the pump, microwave and sideband modes. The modes overlap is represented by the integral in the numerator. Integrals in the denominator have meaning of the mode volumes. Field distribution of WGM is found analytically only for resonators with a spherical symmetry, however a good approximation is available in case of a disk-shape resonators for resonances in the optical domain, where the resonator is electrically large [14]. The microwave resonances can be found with aid of full-wave simulators. WGMs are classified due to field distribution inside the resonator and are described by the number of zeros in the radial direction q, the number of maximums in the azimuthal direction $\pm m$, where the sign depends on the clockwise or counter clockwise direction of propagation, and the number of maximums in the polar direction $p = m - l + 1$, where l is the polar number [8]. Due to rotational symmetry of the resonator we distinguish azimuthal dependence of the eigenfunction

$$\mathbf{\Psi}(\mathrm{r}, \Theta, \varphi), = \mathbf{\Psi}'(r, \Theta)\mathrm{e}^{\pm im\varphi}$$

The modes overlap integral takes non-zero value only when angular momenta condition is preserved. The condition is known as phase matching and is given by

$$m_p - m_s = \pm m$$

where m_p, m_s and m are pump, sideband and microwave signal azimuthal numbers, respectively. It is the only phase matching condition in the most common case $|m| = l$. Modes with higher polar mode order have lower quality factors and additional requirements for phase matching that must be taken into account [8]. An example of microwave signal mode in a mm-size disk resonator is depicted in Fig. 2.

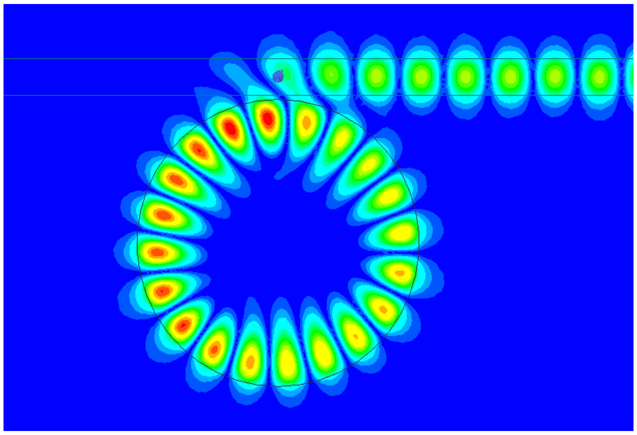

Figure 2: Example of field distribution of a whispering gallery mode for an azimuthal mode number $m = 10$.

3. SENSITIVITY

Signal power measured by radiometers can be expressed as its equivalent temperature T_A (Rayleigh-Jeans units). The sensitivity of the radiometer is given by a standard deviation of the signal power ΔT. Noise performance of the radiometer depends on its thermal noise as well as on photon shot noise described by Mandel's formula [15]. Semi-classical radiometer equation considers both and is given by [16]

$$\Delta T = \frac{T_A + T_e}{\sqrt{\Delta v \Delta t}} \left(1 + \frac{hv}{\eta k_B (T_A + T_e)}\right)^{1/2}$$

where T_e is an effective temperature of the thermal noise, Δv is bandwidth of the upconverted signal and Δt is integration time. The photon shot noise contribution scales with $\eta^{-1/2}$ and might be significant for low photon conversion efficiency. The semi-classical formula converges to the classical radiometer equation for $hv \ll \mu k_B (T_A + T_e)$. A competitiveness of presented radiometer relies on radiative cooling of WGMs. It was derived in [7] that the effective temperature of the upconverted thermal noise can be significantly lower than the physical temperature of the radiometer when the microwave mode is overcoupled to the resonator. Relation between effective noise temperature and the physical temperature T_{phys} is given by

$$T_e = \left[\frac{(1 - a^2(1 - |t|^2)) \ln (a^{-2})}{(1 - a^2)|t|^2} - 1\right] T_{phys}$$

where, $|t|$ is coupling efficiency strength (see Fig. 1) and

$$a^2 = \exp (-2\pi |m| / Q)$$

is roundtrip power attenuation of the mode with Q as its quality factor. The effective thermal noise temperature is plotted as a function of coupling efficiency strength for physical temperature 300 K in Fig. 3. It was shown in [7, 16] that for high conversion efficiency $\eta = 10^{-2}$, estimated sensitivity of the proposed radiometer scheme operating at room temperature is comparable or possible better than state-of-the-art cooled mm/submm-wave LNAs. Proposed efficiency has not been presented yet. However, it could be achieved by improving modes overlap and considering resonator material with higher nonlinearities.

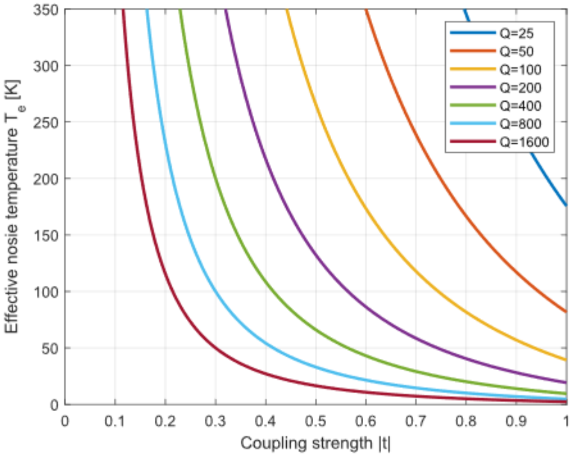

Figure 3: Effective thermal noise temperature as a function of coupling strength $|t|$ plotted for few values of microwave mode quality factors.

4. EXPERIMENT

The conducted experiment is focused on optimizing resonator shape to fulfil phase-matching condition and thus maximize the photon conversion efficiency. Due to manufacturing tolerance limits, phase-matching was optimized by changing iteratively a radius of a disk-shape resonator. The upconversion scheme was tested at 80 GHz using the setup presented in Fig. 4. The central component in the setup is z-cut lithium niobite (LiNbO3) resonator with a diameter of 5.66 mm. The microwave signal is generated by photomixing two telecom lasers relatively detuned by the required frequency, then it is coupled to a dielectric waveguide rod made of gallium arsenide [17] and so on to the resonator. To control the microwave spectrum of the resonator a photomixer receiver is set up. It is synchronized with the emitter to share the same beat frequency. The pump signal is generated by a 1550 nm tuneable laser polarized and filtered by amplified spontaneous emission (ASE) filter. The filter is used to decrease noise generated by the laser around the expected frequency of the sideband. An electro-optic modulator is a part of a Pound-Drever-Hall scheme and eliminates the need of temperature stabilization as it locks the laser to the resonance frequency. Laser is focused by a GRIN lens and coupled to resonator via a diamond prism. The upconverted signal within an outcoming pump is outcoupled through the same prism, focused with a second GRIN lens, coupled to an optical fibre and guided to an optical spectrum analyser (OSA) to characterize the performance of the system. The exact optical mode numbers in Eq. (1) are difficult to define, thus in practice it is more convenient to use free spectral range (FSR), defined as the difference of two consecutive resonant frequencies of the optical modes. Thus, we can rewrite the phase-match condition as a single equation given by

$$v = |m| \times FSR$$

In the experiment, phase-matching is achieved by polishing the resonator iteratively reducing its radius. As a result, both microwave signal resonant frequency v and FSR are slightly changed. The tuning steps are presented in Fig. 5. The intersection point of two lines represents phase-matching. Final measurements of the optical modes show 50 % of coupling efficiency, free spectral range FSR=7.883 GHz and bandwidth of 2.45 MHz what gives the intrinsic quality factor around $Q \approx 1.6 \times 10^8$. The microwave mode is coupled with efficiency 90% and the microwave mode resonance frequency is 78.88 GHz. The mode has an intrinsic quality factor around 400 and a power enhancement $F \approx 6$, when critically coupled. For the SFG process and the power of the pump from the range of 0.03-0.33 mW, the normalized photon conversion efficiency was measured $\eta/P_p = (2.5 \pm 0.2) \times 10^{-5}\, mW^{-1}$. The result surpasses by two orders of magnitude so far, the reported conversion efficiencies using WGM resonators at mm-waves [18]. It is also 30 times higher than state-of-the-art ultra-wideband lithium niobite waveguide phase modulators [19].

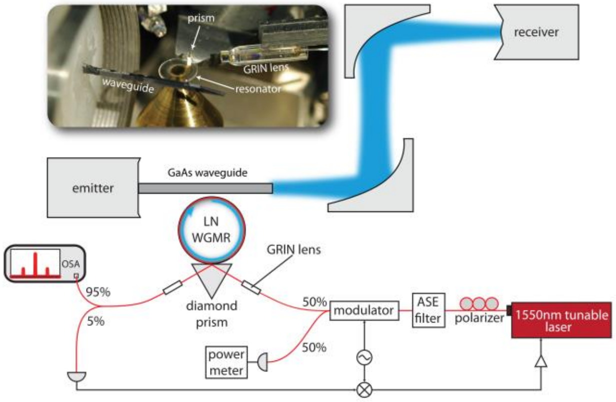

Figure 4: Setup used in an upconversion experiment.

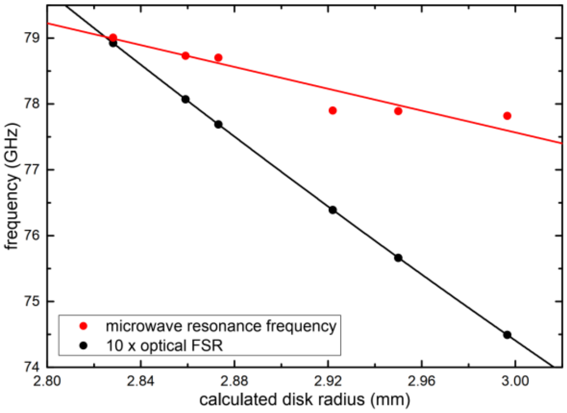

Figure 5: Visualization of iterative steps in phase matching. The phase matching was achieved by polishing the crystal and reducing its radius. The process increases microwave resonance frequency as well as FSR of the optical mode. A difference in changes rate makes it possible to achieve phase matching at the lines cross point.

5. CONCLUSIONS

In this paper we presented alternative radiometer that does not require cooling down to cryogenic temperature. Eliminating the need of using cryostat makes a payload compact, improves its reliability and therefore it might extend satellite's mission lifetime. The proposed solution can be especially useful for microwave hyperspectral sensing due to requirement of narrow-bandwidth channels. The selectivity is provided by electro-optic upconverter based on nonlinear WGM resonators that are characterized by extremely high-Q of the order of 10^8 at optical frequencies. High sensitivity of the radiometer operating at room temperature is provided by radiative cooling the overcoupled microwave mode. To compete with state-of-the-art LNAs the photon conversion efficiency must be improved from 10^{-5}, measured in the experiment to 10^{-2}. The efficiency may be increased by providing better modes overlap and considering materials with higher nonlinearity.

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