Low SWaP, High performance, 94GHz RF-photonic radar receiver

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***Abstract*—A resonant photonic receiver is under development to efficiently upconvert a weak microwave signal, such as a return signal of a millimeter-wave radar, to optical frequency domain and then transfer this signal to an intermediate microwave frequency, convenient for further processing. Such a process is far less demanding in terms of the instrument size, weight and power than the direct high frequency microwave detection and down conversion. The resonant photonic receiver facilitates an amplification of the signal power with low noise temperature which improved the instrument sensitivity relative to the stateof-the-art. A combination of these factors will enable a new generation of ultra-compact radars suitable for Smallsat and Cubesat form-factors. We report the theoretical analysis and numeric simulations justifying the photonic approach to millimeter-wave detection based on high-quality nonlinear optical resonators, as well as the preliminary tests results.**

***Index Terms*—millimeter-waves, photonic receiver, microresonator, nonlinear optical conversion.**

I. Introduction and principles of operation

Millimeter-wave spaceborne radars are particularly useful for making detailed and sensitive measurements time-varying atmospheric structure, clouds and precipitation, among other applications. However, the existing spaceborne radar systems that are geared towards that goal around Earth (such as GPM, CloudSat etc) are large instruments with significant size, weight, power consumption requirements and thus cost. Such architectures don't lend themselves to missions targeting low-cost, low power measurements. The RF-photonics based radar receiver addresses this unmet need for high-performance, compact, millimeter-wave radars, compatible with Smallsat and Cubesat size, weight and power constraints while providing highly sensitive measurements of atmospheric phenomenon.

The photonic receiver described here serves as a front end to a radar system addressing two of the most challenging performance aspects, coherent downconversion with very low thermal noise (and thus higher SNR at low instrument SWaP) and a high-quality W-band local oscillator (improving measurement dynamic range). In this paper, we present the development effort of a receiver which is being developed for an Earth orbiting cloud radar concept but is generally applicable to atmospheric structure studies for a wide range of atmospheres. The receiver leverages coherent up-conversion of a W-band signal (94 GHz) to optical domain (1560 nm) inside an optical resonator with a gigantic quality factor Q. The resonator is fabricated from an electro-optical material which enables the interaction between the W-band signal and a monochromatic optical pump. The signal is thereby upconverted to the optical frequency domain and is processed optically [1]–[17]. Since the optical detection is much less affected by thermal noise than the microwave detection, this approach leads to a superior performance in terms of the noise figure and sensitivity, compared to a pure electronic detection of the W-band signal. Moreover, since the optical parts have small size and require less power to operate, the photonic system has much smaller size and power consumption.

High-Q optical micro-resonators based on the whispering gallery modes (WGM) have been successfully used for various optical and microwave photonic applications, including microwave receivers simultaneously supporting optical WGMs and microwave modes of various nature [1], [2], [18]–[26]. The efficiency and performance of these receivers scales as Q^2Q_M [1], where Q_M is the loaded quality factor of the microwave mode. But it does not fundamentally dependent on the microwave frequency, which is why the nonlinear WGM resonators have been used in photonic front-end receivers ranging from X- to Ka- and W-bands. Theoretically, for the lithium niobate and lithium tantalate WGM-based receivers this range can be extended up to 1 THz, as determined by the transparency range of these crystals.

The noise temperature of even the best demonstrated photonic receivers has so far greatly exceeded the ambient temperature. This can be attributed to their sub-optimal design. Here we describe an optimized design of a 94 GHz spaceborne radar that can achieve the noise temperature below the ambient 300 K, leading to an approximately 4 dB better sensitivity than typical W-band radar implementations. The size of the physics package of this instrument can be made as small as a few cubic centimeters, with the power consumption below one Watt.

The receiver architecture is illustrated in Figure 1. The Wband signal is collected into a horn antenna (not shown in the diagram) and sent down the standard WR10 waveguide towards the optical WGM resonator with a radius R. The waveguide ends with a microwave cavity whose resonance frequency can be tuned with a back-side plunger. This cavity builds up the microwave field. Its geometry is optimized in such a way that the anti-node corresponds to a field concentrator pin, which creates a strong local field at the surface of the optical resonator. This field permeates inside the WGM resonator where it interacts with optical mode. This mode is excited through the coupling prism by the light supplied through the input fiber and collimated with a GRIN lens. A similar assembly collects the output light, which now has not only the pump spectral line, but also a sideband produced by the W-band signal. This sideband is then detected in an optical heterodyne setup (not shown) and downconverted to the IF domain.

II. Theoretical Performance Model

Different microwave receivers configurations discussed in the references above rely on different relative orientations

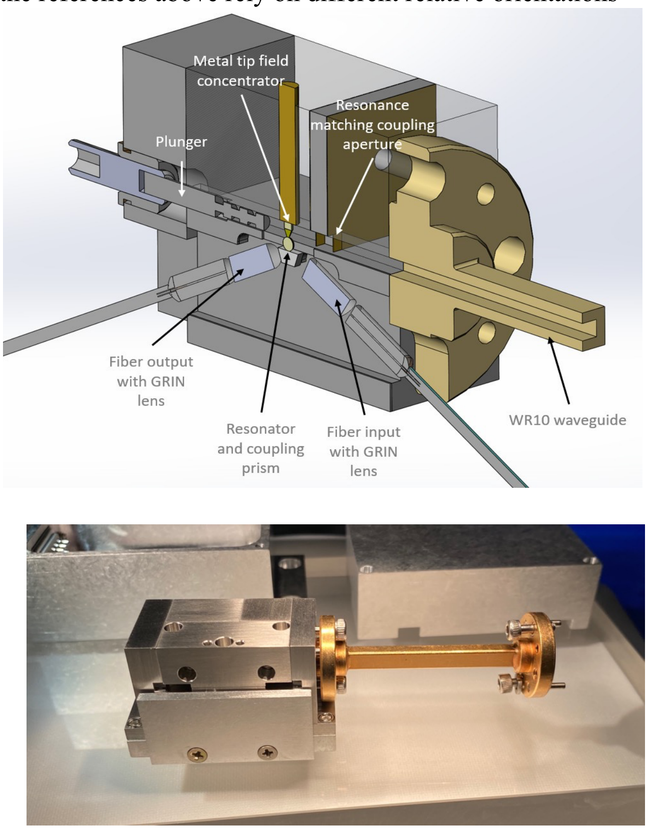

Fig. 1. Conceptual design of the W-band microwave photonic receiver (top) and physical realization of the entire receiver package attached to a standard 94GHz WR-10v waveguide

of the microwave, pump, and optical signal polarizations. Our approach is based on orthogonaly polarized pump and signal WGMs: one polarized in the resonator plane (the TM mode), the other polarized perpendicularly to this plane (the TE mode). This configuration allows us to tune the pumpsignal frequency difference to the desired W-band frequency. This is possible due to different temperature dependencies of the ordinary index of refraction n_o mainly affecting the TM mode, and the extraordinary index of refraction n_e mainly affecting the TE mode. The TE and TM optical modes efficiently interact with the RF field polarized in-plane. This interaction is mediated by the electro-optic tensor coefficient $r_{42} = r_{51}$, which is significant in both lithium niobate and lithium tantalate.

The physics of optical upconversion for this fields configuration is discussed in detail in [27]. To summarize this analysis, the key parameter responsible for both the conversion efficiency and the noise temperature is shown to be the conversion rate g of microwave to optical photons, found as

$$g = n_o n_e r_{51} \frac{2\pi c}{\lambda} \int_V \Psi^*_{TE}(\vec{r}) \Psi_{TM}(\vec{r}) E_{RF}(\vec{r})\, dV. \quad (1)$$

Here λ is the optical pump wavelength in vacuum, $\Psi_{TE,TM}$ are the TE and TM normalized WGM eigenfunctions, and $\vec{E}_{RF}$ is the radial projection of the microwave electric field. This field is simulated for our microwave cavity using Ansys High Frequency Structure Solver (HFSS).

The analytical approximations for the optical WGM eigenfunctions are well known [28]. They are confined so tightly in the equatorial region of the WGM resonator, that the $E_{RF}(\vec{r})$ can be treated as a constant in that region. Then, neglecting the difference in the pump and signal mode refraction indices, mode numbers and wavelengths, and using the normalization property of Ψ_{TE} and Ψ_{TM}, we find

$$g \approx n_o n_e r_{51} \frac{c}{\lambda} \int_{-\pi}^{\pi} \cos(\Delta m \phi) E_{RF}(w_0, 0, \phi) d\phi. \quad (2)$$

Here $\Delta m = m_{TE} - m_{TM}$ is the mismatch between the pump and signal modes orbital numbers, and

$$w_0 \approx 0.308 \left(\frac{R\lambda^2}{n^2} \right)^{1/3} \quad (3)$$

is the depth of the WGM peak intensity beneath the resonator surface. The factor $\cos(\Delta m\phi)$ in the integral (2) points at the necessity to optimize the field concentrator width along the WGM resonator.

The conversion rate g determines the maximum contrast of the optical signal sideband relative to the pump power

$$\eta_s = \frac{P_s}{P_0} \frac{4g^2}{\gamma_a \gamma_b,} \quad (4)$$

where γ_a and γ_b are the loaded linewidths for the pump and signal WGMs.

The optical heterodyne measurement is performed by mixing the optical signal with a local oscillator on a balanced photodiode. The beat note power generated in such a measurement is

$$P_{RF\ out} = \rho \mathcal{R}^2 P_0 P_{LO} \eta_s = \rho \mathcal{R}^2 P_0 P_{LO} \frac{4g^2}{\gamma_a \gamma_b,} \quad (5)$$

where R is the photodiode responsivity and ρ is the photodiode circuit impedance. The photonic gain G can be introduced as the ratio of this power to the power of the W-band signal $P_{RF\ in}$ supplied from the waveguide:

$$G = \frac{P_{RF\ out}}{P_{RF\ in}.} \quad (6)$$

The signal and noise in a balanced heterodyne measurement in a weak signal regime are found as [?]

$$S_{out} = 4\rho \mathcal{R}^2 P_{LO} P_s = 4 G P_{RF\ in},$$
$$N_{out} = \left[k_B T + 2\hbar\omega\rho \mathcal{R}^2 P_{LO} \right] \Delta F, \quad (7)$$

respectively. Here ΔF is the reception bandwidth, which is the smallest of the WGM bandwidth and the bandwidth of the microwave cavity, and T is the receiver ambient temperature.

The noise is determined by a combination of the Johnson–Nyquist (thermal) noise and the optical shot noise. Here we took a conservative approach by identifying the noise with the full power of the thermal fluctuations within a given bandwidth. Alternatively, the mean-value of the additive noise can sometimes be subtracted, providing a new zero level for the signal measurement. Then only the fluctuations of this power power around its mean-value mask the signal and should be treated as noise. This approach, explored in [12], [16], can potentially provide an even better sensitivity. The receiver sensitivity is found from (7) as

$$\frac{P_{RF\ min}}{\Delta F} = \frac{k_B T}{4G} + \frac{\gamma_a \gamma_b \alpha_W}{8g^2}\hbar\omega. \quad (8)$$

The shot noise contribution to (8) can be reduced by increasing the conversion rate g by increasing the pump power P_0. Then the received noise temperature can be brought below the ambient temperature if $G > 0.25$ for a balanced heterodyne measurement (or $G > 1$ for a single-detector measurement). Reaching this value of the photonic gain is an important benchmark that has not yet been reached.

III. Comparison to the sate of the art

To derive the numeric estimates from the above analysis and compare then again the best existing W-band radars we take the parameter values listed in Table I. The calculation results for the main performance parameters introduced above are also listed in the table.

TABLE I
THE PARAMETERS USED IN THE NUMERIC ESTIMATES AND MAIN PREDICTED CHARACTERISTICS

Parameter	Symbol	Value
Optical wavelength	λ	1558.6 nm
Resonator radius	R	490 μm
Rim radius	r	104 μm
Ordinary refractive index	n_o	2.1189
Extraordinary refractive index	n_e	2.1231
Electro-optic coefficient	r_{51}	20 pm/V
WGM field depth	w_0	2 μm
TM coupling rate	γ_{TM}	2×10^7 rad/s
TE coupling rate	γ_{TE}	4×10^8 rad/s
Pump power	P_0	10 mW
LO power	P_{LO}	2 mW
RF impedance	ρ	50 Ω
Photodiode responsivity	R	0.9 A/W
Differential mode number	Δm	7
Predicted Performance	**Symbol**	**Value**
Conversion rate	g	3.91×10^9 1/s
Photonic gain	G	6.3
Shot noise contribution		$0.19k_BT$ W/Hz
Thermal noise contribution		$0.04k_BT$ W/Hz
Receiver Sensitivity	$P_{RFmin}/\Delta F$	$0.23k_BT$ W/Hz

An additional important figure of merit that can be evaluated is the microwave-to-optics conversion efficiency in terms of the number of photons:

$$\eta_N = \frac{1}{P_0}\frac{\hbar\omega_{RF}}{P_{RF\ in}}\frac{P_s}{\hbar\omega}. \quad (9)$$

Using the values from Table I we predict $\eta_N \approx 0.019$ mW^{-1} is about 7 times higher than the experimental result reported in [11], or about 4 times higher than the experimental result reported in [15].

To compare the result from Table I with the state of the art we note that in typical weather radars the bandwidth ΔF is a few MHz, while the RF-electronics based receivers have a noise figure of 5 to 10dB [?], [?]. The typical single-pulse detectable power for such a radar is approximately -97 dBm at 300 K ambient temperature. For a photonic receiver, the minimum detectable power for the same bandwidth can be as low as -110 dBm. An increase of sensitivity by an order of magnitude while decreasing overall instrument size is very appealing for compact radars.

IV. WGM resonator

An optical WGM resonator fabricated from an electrooptical crystal is the key element of the proposed photonic receiver. The crucial requirements to this element include a high quality factor Q and large electro-optic tensor element r_{51}. A lithium tantalate crystal is known to satisfy both requirements. Furthermore, the resonator fabricated from this material must support the fundamental TE and TM WGMs with the orbital numbers m that are not too different. If the orbital number difference Δm is large, the field concentrator pin should be very short in the latitudinal direction ϕ according to (2), which will adversely affect the conversion efficiency.

In a very crude approximation $\Delta m = 2\pi R(n_o - n_e)/\lambda$, which puts an upper limit on the resonator size. We used a more accurate WGM dispersion equations [29], also taking into account the chromatic and temperature dispersion of the indices n_o and n_e, to find the resonator radii corresponding to a reasonably small Δm. As a further condition, the difference between the TE and TM WGM frequencies was required to match the target W-band signal frequency, 94.05 GHz, at a convenient temperature $T_0 = 35$°C and the pump wavelength $\lambda_0 = 1558.6$ nm. A solution to this problem comes as a list of optimal R values associated with different Δm [27]. For example $\Delta m = 6$ corresponds to $R \approx 414\mu$m, $\Delta m = 7$ corresponds to $R \approx 495\mu$m, and so on. The error margins on these values depends on how far one can afford to tune the pump wavelength and the resonator temperature. Typically a few microns radius error requires a few degrees change to recover the desired frequency difference.

In Figure 2 we show a test resonators fabricated from lithium tantalate. It has the radius $R = 429 \pm 2\mu$m, which is reasonably close to the $\Delta m = 6$ optimal radius. Its rim radius was made approximately 90 μm to provide the optimal coupling with an incident TEM00 beam [4]. This resonator was coupled to a test laser with 1550 nm central wavelength, and both TE and TM

WGM spectra were observed. We measured the intrinsic linewidths $\gamma_{TM}^{(0)} \approx 3.4 \times 10^6$ rad/s and $\gamma_{TE}^{(0)} \approx 2.5 \times 10^6$ rad/s. These are significantly narrower linewidths than projected in Table I, indicating a higher Q factor ($Q \approx 3.5 \times 10^8$). This suggests that a receiver using this resonator may surpass the expectations outlined above.

V. Conclusions

A photonic receiver described in this work can serve as a front end for a W-band compact radar compatible with space applications. This receiver performs a coherent, low-noise, frequency-resolving conversion of the returned radar signal to the near-infrared optical signal. Detecting the optical signal instead of the W-band signal entails great practical advantages, reducing the radar's noise, size and power consumption.

Basing on conservative estimates and modest assumptions, we predict the noise temperature at the level of 0.35 of the ambient temperature, on the absolute temperature scale. For the ambient temperature of 300 K the receiver noise temperature of 69 K is expected without using any cooling.

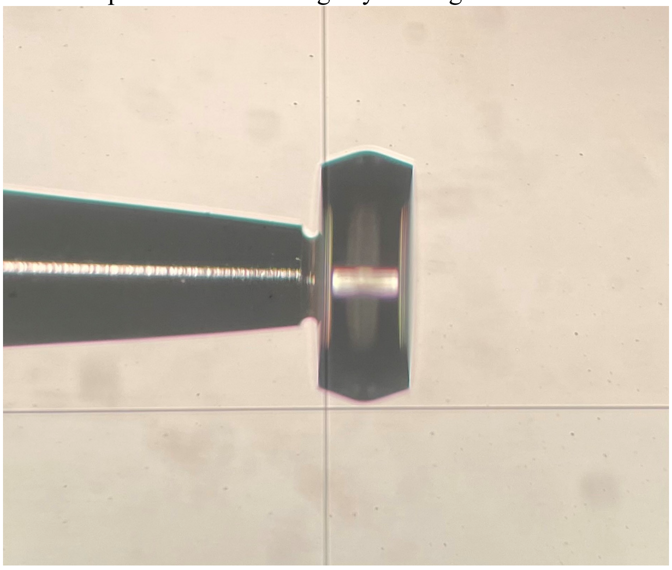

Fig. 2. A test WGM resonator made from lithium tantalate is temporarily mounted on a needle tip for inspection and cleaning.

This gives a factor of 8.7 sensitivity improvement compared to a typical W-band low-noise amplifier with the noise temperature of around 600 K. The combination of the size, power and sensitivity factors makes our receiver appealing for applications on Smallsats and Cubesats platforms.

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