G-Band Metamaterial-Based Circulator for FCC-Compliant Space-to-Earth Communication

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***Abstract*—A metamaterial-based circulator operating at G-band is presented for the purpose of high-data-rate space-to-Earth communication. The circulator is designed to be equipped on a CubeSat using a single antenna, integrating a metamaterial within an interface of three WR3 waveguides measuring 3 mm in length per waveguide. The isolation is achieved between transmitting (downlink) signals at 295 GHz and reception (uplink) at 218 GHz. The frequencies are chosen in accordance with FCC regulations and aim to provide a high-data-rate download link for CubeSats deployed in non-terrestrial networks.**

***Index Terms*—Terahertz Space Communication; Metamaterial-based Circulator; Terahertz CubeSat Networks**

I. Introduction

With the inclination towards high-data-rate space-based internet and the increasing demand of efficient communication across scientific instruments, terahertz (THz)-band communication (0.1-10 THz) has been explored as a candidate for space communication leveraging existing technology. The potential for high data rates in the terahertz band is enabled by the high available bandwidth, as well as existing technology that can support such bandwidth [1]. Furthermore, THz CubeSat networks have been explored as part of the vision for sixth-generation (6G) wireless communication through multi Giga-bit-per-second (Gbps) inter-satellite links, with physical layer and medium access control solutions already being explored [2]. In our previous work, THz communication was studied extensively for inter-satellite as well as space-to-Earth links in an end-to-end simulation, demonstrating multi-Gbps in both scenarios when high antenna gain is available [3]. The simulation was performed in compliance with FCC regulations, crowning 217.5 GHz and 295 GHz as ideal central frequencies for uplink and downlink respectively using 8320 small satellites.

In order to deploy a massive number of satellites, reductions in size, weight, and power must be leveraged in the form of CubeSats, which have been considered a staple of 6G communication and a key element of the increasingly-popular non-terrestrial networks (NTN) [2]. Similarly, in order to fully leverage size reductions, CubeSats would ideally use a single antenna for transmission and reception; given that THz antennas will require high gain, using a single antenna would majorly contribute to saving real estate.

The interest in saving real estate by duplexing transceivers and, therefore, use a single antenna for transmission and reception has long been present in the radar community. Recently, with the development of the first active weather radar operating within G-band (110 GHz to 300 GHz), full-duplex capability has been obtained thanks to the use of quasi-optical circular polarization duplexers [4], [5]. These encode transmission and reception signals in the horitzontal and vertical polarizations, respectively, for full duplexing. This approach, however, is not appealing from a communications perspective since multiplexing capabilities through the polarizations of the transmitted wave would be lost. Thus, the objective then is to design a G-band circulator that satisfies the compactness and power criteria of terahertz CubeSat for high-bandwidth communication.

Achieving full duplexing capabilities through the use of circulators has been studied for satellite communications at lower frequencies. Traditional circulator designs targeting modest microwave frequencies are based on semiconductor devices, in intermediate bands (i.e. Ku/Ka band), ferrite based devices are used almost exclusively. These kind of circulators are based on Turnstile designs implementing Okada resonators [6], [7], which mainly consist of two ferrite disks of identical geometry and dimensions separated by a dielectric material. Ferrite based circulators are being designed for wide band space applications at Ku band (25% bandwidth) [8] and at Ka band (13% bandwidth) [9]. However, the implementation of this type of circulator at frequencies close to the THz band is technically challenging; ferrite components suffer from high cost, high weight, and incompatibility with an integrated circuit design, which are critical restrictions when considering Cubesats dimensions. Here, research in the field of metamaterials has enabled the creation of broadband circulators at frequencies of tens of GHz using spoof surface plasmon polaritons (SSPPs) [10], [11]. Near-zero-index metamaterials (NZIMs) have been investigated for the design of magnetless circulators [7] in which controlling the properties of EM waves (propagation, absorption and polarization) is possible without the need of any external magnetic field, although using a restrictive angle-selective methodology.

In this paper, we propose a frequency-selective solution leveraging a frequency-dependant metamaterial as explored in the design methodology.

II. Design Methodology

In order to achieve simultaneous transmission and reception, the feeding network of the dual-band antenna proposed in [12] is realized in Fig. 1, where a circulator serves to isolate between the transmitting and receiving frequencies of a super-heterodyne terahertz system similar to the one in [1].

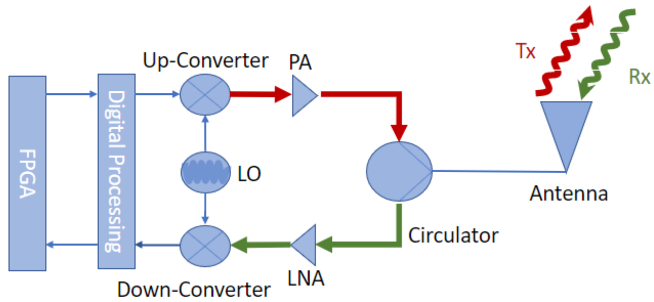

Fig. 1. The working principle of the dual band antenna, enabled by the proposed circulator.

A commercially-available WR3 waveguide is utilized as to allow both 218 GHz and 295 GHz signals to operate in accordance with the rectangular waveguide cutoff frequency given by

$$f_c = \frac{c}{2}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}, \tag{1}$$

where a is width and b is thickness of the waveguide, m and n are the mode propagation numbers and c is speed of light inside the waveguide. The metamaterial is then inserted at the interface of the receiving waveguide and the waveguide junction as visualized in Fig. 2. The metamaterial's special behavior, mainly frequency-dependent complex-valued permittivity, is defined by

$$\epsilon(\omega) = \epsilon'(\omega) + j\epsilon''(\omega) = \epsilon_r(\omega)\epsilon_0 + j\frac{\sigma(\omega)}{\omega}, \tag{2}$$

where ω is the wave frequency, ϵ is effective permittivity, ϵ_r is relative permittivity of the material, ϵ_0 is free-space permittivity, and σ is conductivity of the material.

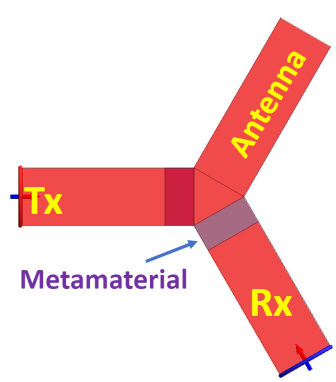

Fig. 2. The working principle of the circulator, interfacing the three WR3 waveguides.

III. Results

The results show the fundamental mode waves propagating from the waveguide source port throughout the circulator, which is the feeding waveguide (Tx) for the transmitter and the antenna for the receiver. Figure 3 shows the surface currents across the circulator for the transmit and receive cases, proving the metamaterial effective at achieving isolation. The reflection coefficient for the transmit case is -21 dB and -20 dB for reception. The simulations are completed using Altair FEKO software utilizing the multilevel fast multipode method (MLFMM). The next step is to develop and simulate an integrated full-duplex communication system involving the antenna deploying from the CubeSat.

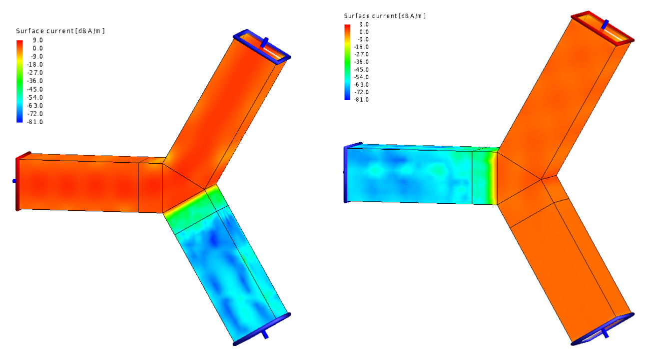

Fig. 3. The surface currents present on the waveguides in transmission mode, showing behavior at 218 GHz (left side) and at 295 GHz (right side).

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