A Compact Dual-Channel Transceiver for Long-Range Passive Embedded Monitoring

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***Abstract*— This document describes the design of a compact, 3-D dual-channel transceiver for passive wireless sensor node design. The transceiver contains two harmonic repeaters, one to be connected to a sensor and one to provide a reference signal for remote channel calibration and node identification. Each repeater consists of a diode-based frequency doubler and conjugate-matched receive and transmit meandered monopole antennas. The sensing repeater operates by receiving a 2.4 GHz signal and re-radiating a modulated 4.8 GHz return signal. The reference and sensing repeaters are optimized for RF input power level ranges between -30 and -20 dBm with zero DC power. The diagonal of the transceiver measures 0.25 λ at 2.4 GHz and its measured conversion gain (CG) is -12.4 dB with a 2% 3 dB CG bandwidth at -20 dBm input power. With this performance the communication range using an interrogator with a 2 W EIRP is > 40 m in a free space environment.**

I. INTRODUCTION

Structural health monitoring [1], would benefit from sensing that is deeply embedded in the environment for an extended period of time. For such applications, it is desirable that the sensing device 1) be passive for long operating lifetime, 2) has a compact geometry to avoid compromising the structural integrity, 3) has omni-directional radiation patterns to simplify the communication process, and 4) operates at low RF activation power level and be energy-efficient to expand the communication range.

The use of harmonic back-scatter from a passive node is an approach that provides a long communication range at low RF power, Fig.1. This approach has found use in different tracking systems [2, 3] and recently has been proposed for embedded passive sensing [4]. In [4], the design achieves a communication range of 45 m using a source with an effective isotropic radiated power (EIRP) of 2W. This design combines the RF interrogation technique with a diode-based frequency doubler to return the second harmonic of the interrogation signal, avoiding the fundamental signal clutter and transmitter-receiver bleed through. These issues are of particular concern for embedded applications and can significantly limit the interrogation range.

The main objective for the dual-channel harmonic transceiver described herein is to enable remote channel calibration and node identification in a compact form factor. Both of these capabilities may be critical for practical implementation of these passive nodes. Calibration of the communications channel is necessary whenever the sensor output is directly correlated with the amplitude of the back-scatter signal, e.g. in the case of a temperature sensor, especially if the interrogator-to-node orientation is not constant in time. Some form of node identification is also necessary especially when multiple nodes fall into the beamwidth of the interrogator antenna, a situation that is likely to occur given the relatively long communications range of the harmonic transceivers. These capabilities are possible by combining two narrowband channels – one acting as a reference channel and one as the sensing channel – that have a frequency offset into a single transceiver. To the best of the authors' knowledge, the developed transceiver is the first completely passive design with built-in passive remote channel calibration and identification capability. The performance and size of the proposed design compare well with previously published passive, single channel harmonic repeaters. To address the fabrication complexity, improve the design reliability, and reduce cost and weight the use of 3-D digital printing is investigated.

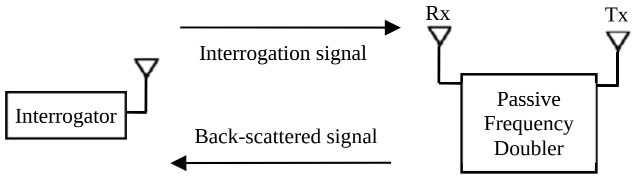

Fig. 1. Block diagram for passive wireless sensor being interrogated with an RF signal.

II. PROJECT OUTCOMES

The transceiver developed in this work is submitted for publication [5] and shown in Fig.2. The sensing and reference repeaters each consists of receive and transmit monopole antennas rising vertically off a ground plane, along with a frequency doubler. The sensing repeater operates by receiving a signal at 2.4 GHz and transmitting a signal back at 4.8 GHz that may be modulated by a sensor output, while the reference repeater operates at 2.75/5.5 GHz for this demonstration. The diagonal of the entire design measures 0.25 λ at 2.4 GHz. The antennas are designed to be conjugate-matched to the doubler input/output impedances to maximize the conversion efficiency. Each antenna is linearly polarized along the Z-axis and demonstrates omni-directional pattern in the XY-plane. The gain variation over the receive antenna H-plane is 1.6 dB while it is 2 dB for the transmit antenna. The receive antenna peak gain is 0.9 dBi with a simulated radiation efficiency of

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78.5%. The peak gain and radiation efficiency of the transmit antenna are 1.1 dBi and 67%, respectively.

The transceiver performance was characterized wirelessly inside an anechoic chamber at a distance of 1 m, where the transceiver receives the f_1 signal generated using a vector network analyzer and transmits a return signal at $2\cdot f_1$ measured using a spectrum analyzer. The measured CG (defined here as the ratio of the return power at $2\cdot f_1$ to the received power at f_1) of the sensing repeater for an RF input power of -20 dBm is -12.4 dB while it is -8 dB for the reference repeater.

Amplitude modulation can be imparted by connecting a sensor that generates an AC voltage to the doubler circuit, as demonstrated in [6]. The applied voltage changes the diode impedance which affects the CG of the transceiver and the return power level. For this purpose a DC bias network is included in the doubler circuit design.

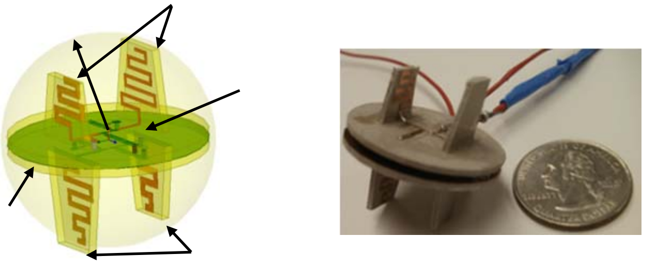

Fig. 2. A CAD view of the proposed transceiver with a hypothetical sphere of 15.5 mm radius (left) and a photograph of the fabricated design (right).

Fig.3 illustrates how the calibration can be performed using the presented design. The measurement is performed by varying the interrogation signal frequency and applying a bias voltage to the sensing repeater Fig.3 (left). The voltage source represents a sensor output in this demonstration. Fig.3 (right) illustrates the measured return power level at f_1 of 2.4 GHz and f_2 of 2.75 GHz for different applied bias voltage to the sensing repeater and different received power. As seen, when interrogating the transceiver with a signal frequency of 2.75 GHz, the reference repeater provides a nearly constant return signal at $2\cdot f_2$ of 5.5 GHz that is unaffected by the bias on the sensing repeater. Conversely, interrogating the transceiver with a signal frequency f_1 of 2.4 GHz provides a return signal at $2\cdot f_1$ of 4.8 GHz that is highly sensitive to the applied DC voltage; 0.1 V bias decreases the return signal by > 16 dB. By subtracting the amplitude of the 5.5 GHz return signal from the 4.8 GHz return signal, the modulated return signal can be corrected for channel effects, in practice providing a calibrated sensor reading. The reference signal can also be used to identify the node based on frequency diversity as presented in [5].

The use of 3-D digital printing is also investigated in this project. Fig.4 illustrates the 3-D printed transceiver. The substrate material is Acrylonitrile Butadiene Styrene plus (ABSplus) and the conductive material is Dupont CB-028, a thick film silver ink. The use of 3-D manufacturing methods addresses issues of design reliability and reduces the fabrication complexity and weight. However, the CG is decreased by 5 dB. The decrease in CG stems primarily from the lower conductivity of the printed silver in comparison to the copper cladding design.

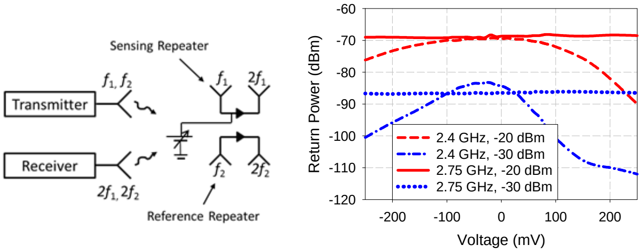

Fig. 3. Illustration of the calibration measurement setup (left) and the measured return power versus voltage applied to the sensing repeater (right) at 2.4 GHz (f_1) and 2.75 GHz (f_2).

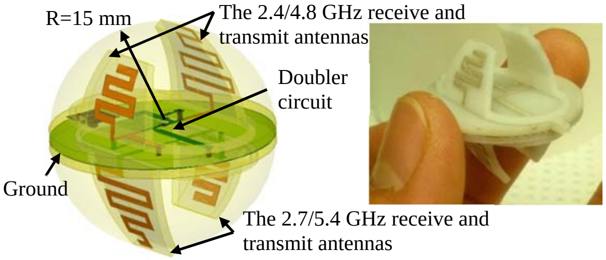

Fig. 4. Illustration of the printed 3-D harmonic transceiver; CAD view with a hypothetical sphere of 15 mm radius (left) and a photograph (right).

III. CAREER PLAN AND FELLOWSHIP IMPACT

My near term goals are to enhance my capabilities and knowledge and gain industry experiences in different microwave engineering applications. Then, I am planning to move to a faculty position at an accredited university where I will be able to run research activities related to real world design problems, and assist other students in achieving their career goals.

The MTT-S fellowship has boosted my motivation to continue my academic research toward the PhD degree and fulfill my career goals. It has provided financial support during my doctoral study and gave me the opportunity to attend the 2013 IMS in Seattle, WA were I had the chance to meet top researchers and scientists from overall the world.

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