Impedance Matching at THz Frequencies: Optimizing Power Transfer in Rectennas

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***Abstract*—A simple and elegant method for matching the impedance of a typical THz self-complementary bowtie antenna to the high-impedance of a nanodiode is proposed. Two twin-lead balanced lines emerging from the antenna feed-point are used to connect the diode, correct for the reactive component of the antenna impedance and compensate the parasitic capacitance of the diode. Numerical simulations considering a model rectenna with a metal-insulator-metal diode showed that impedances up to several kΩ can be effectively matched.**

I. Introduction

Research has been ongoing by numerous groups in the area of electromagnetic energy harvesting and detection in far-infrared/THz using rectennas. A rectenna is an antenna coupled to a rectifier, which converts the fluctuating electromagnetic field to an electrical dc signal. Fast rectifiers, such as the Schottky diode, the metal-insulator-metal (MIM) diode, and more recently the self-switching nanodiode, are often used in these applications [1-4] due to their ability to operate at frequencies well into the terahertz range [1-2]. One of the major drawbacks, however, is the relatively low conversion efficiency (η), caused mainly by the mismatch between the impedance of the antenna (tens to hundreds of Ω) and that of the diode, which is typically as high as several kΩ [4-5]. A matching network is therefore required to match the impedances of the antenna to that of the rectifier in order to maximize the device efficiency. Fig. 1 shows a basic equivalent circuit diagram of a rectenna, with an impedance matching network placed between the antenna and the rectifier.

The conversion efficiency is given as;

$$\eta = \frac{P_{OUT}}{P_{IN}} \tag{1}$$

where P_{OUT} is the rectified output power, and P_{IN} is the input power transmitted by the antenna.

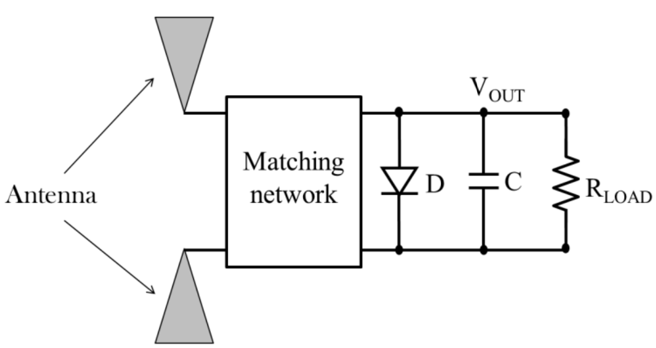

Fig. 1. Basic equivalent circuit diagram of a rectenna with impedance matching network.

This work presents a simple and elegant method for matching the impedance of a typical terahertz bow-tie antenna to a diode with an impedance of several kΩ. The device operates as a high-efficiency THz rectenna, which could be used in a wide range of applications including energy harvesting, detection, and imaging applications.

II. Results

The method for transforming the equivalent antenna impedance seen by the diode relies on two planar twin-lead balance lines connected to the antenna feed-point, as shown in Fig. 2. The function of the top line is that of an open-circuit stub of length L_{STUB}, whose susceptance B_{STUB} is in parallel to the antenna admittance Y_A. The line on the bottom, of length L_{FEED}, connects the diode to the antenna, and transforms the antenna-stub admittance to match the complex conjugate admittance of the diode Y_D^* so that:

$$Y_L = Y_D^* = \left[Y_0\left(\frac{1-\Gamma e^{-2ikL_{FEED}}}{1+\Gamma e^{-2ikL_{FEED}}}\right)\right] \tag{2}$$

where

$$\Gamma = \frac{Y_0 - Y_A - iB_{STUB}}{Y_0 + Y_A + iB_{STUB}}, \tag{3}$$

$$B_{STUB} = Y_0 \tan kL_{STUB}, \tag{4}$$

Γ is the reflection coefficient of the layout, B_{STUB} is the stub susceptance for a line terminated on an open circuit as is the case with the stub utilized. Y_0 and k being the characteristic admittance and phase velocity of the twin-lead balanced lines, respectively.

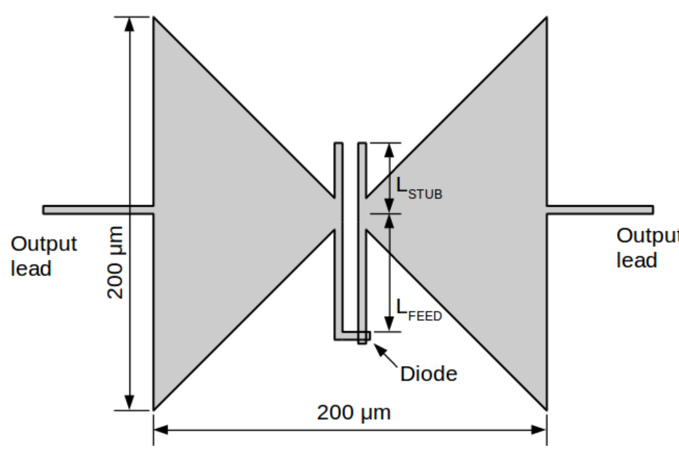

Fig. 2. Layout of the model rectenna and matching network discussed in the text operating at 1 THz. The antenna consists of a self-complementary bow-tie and a rectifier with the parameters of one of our MIM diodes.

As an example, a model rectenna operating at 1 THz was designed with the self-complementary bow-tie antenna shown in Fig. 2, and was modeled with the electrical parameters of gold as the conducting metal sheet on a low-loss glass substrate ($\varepsilon_r \approx 4.8$), using the parameters of one of our MIM diodes as the rectifier. The antenna and twin-lead lines were modeled and simulated using Agilent Advance Design System (ADS).

The computed antenna impedance at 1 THz prior to the introduction of the impedance matching network (i.e. the twin-lead lines) to the layout was $Z_A = 83 + i4\ \Omega$ as can be seen in Fig. 3, whereas the diode impedance was to be $Z_D = 2000 - i10\ \Omega$, estimated using the diode junction area and I-V characteristics. If no matching network were used, an 85% power loss would result due to reflections.

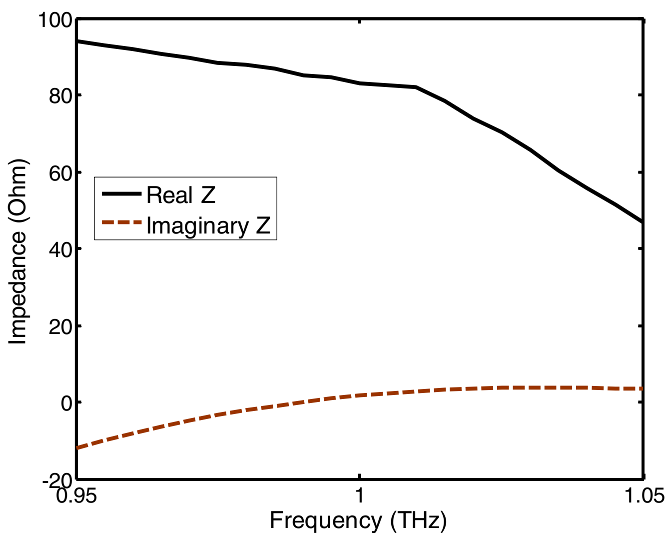

Fig. 3. A plot of the designed self-complementary bow-tie antenna computed impedance as a function of frequency, before embedding twin-lead lines. The impedance $Z_A = 83 + i4\ \Omega$ at 1 THz.

The initial line lengths were determined by solving Eqs. (2)-(4) using Matlab optimisation toolbox. The design was then imported into ADS for the simulation of the impedance and radiation pattern, further optimising the line lengths accounting for the capacitances, as well as fringe capacitances introduced by the line ends, and to study other possible loss mechanisms.

The optimal matching was found for $L_{STUB} = 40\ \mu$m and $L_{FEED} = 45\ \mu$m, dimensions which keep the overall structure compact and introduce only a negligible loss of 0.25 dB in the lines.

The matching network developed was a narrowband, as it is only effective at specific frequencies. As expected, after the introduction of the twin-lead lines (i.e. L_{STUB} and L_{FEED}) in the layout, the antenna exhibits a narrow band behavior where the desired impedance $Z_A = 2000 + i10\ \Omega$ was only obtained at a frequency of 1 THz. This means that the rectenna conversion efficiency will only be maximum at a frequency of 1 THz. A wideband matching network is currently being developed, where a desired impedance can be obtained and sustained in a wide range of frequencies, as this will further make the device more useful in applications such as harvesting of electromagnetic radiation within a wide spectrum, as well as detection and imaging systems.

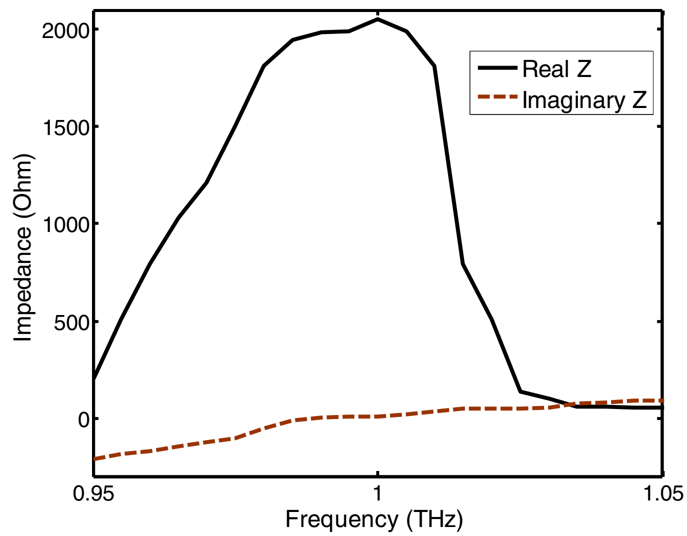

Fig. 4. A plot of the designed self-complementary bow-tie antenna computed impedance as a function of frequency, after embedding twin-lead lines. The impedance $Z_A = 2000 + i10\ \Omega$ at 1 THz.

III. CONCLUSION

A simple and elegant method for matching the high impedance of nanorectifiers is proposed. The method has been applied to a model rectenna, where the matching network overcomes the approximately 85% power loss due to impedance mismatch between antenna and rectifier. This method could be used to dramatically enhance the efficiency in energy harvesting rectennas [4] as well as to maximise the signal-to-noise ratio in detection and imaging systems. The matching network implemented was a narrowband network; however, a wideband matching network is currently being developed to enhance a more effective and efficient performance.

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