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Collection Efficiency for Millimeter and Submillimeter Wave Antenna-coupled Detection

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ABSTRACT

The goal in the design of an efficient and low-noise antenna coupled receiver is to achieve a maximal capture cross section for the incident electromagnetic radiation compared to the dimensions of the sub-wavelength sized sensor loading the antenna. Collection efficiency captures this concept of power output/input and is made up of several sub-efficiencies. In the ideal case all of the available, incident power is collected and transferred to the load. However, many of the fundamental limits of antennas are based on theory describing the transmitting mode, whereas certain questions remain open for receiving antennas. Textbook antenna theory predicts that only 50% of available incident power can be absorbed by an antenna, yet under specific conditions this limitation can be surpassed. Two considerations are presented; (1) fundamental limits on antenna absorption, and (2) practical participation of dissipative media in achieving impedance matching between antenna and load, and the associated performance compromise. Specifically we seek to determine whether antenna-coupled detectors can approach unity absorption efficiency under matched conditions. Further, we identify practical conditions that must be met in order to overcome fundamental limitations that inhibit total absorption. Then antenna loss is split into radiative and dissipative terms in order to identify trade-offs between impedance matching and radiation efficiency.

Keywords: Collection efficiency, receiving antennas, impedance matching.

1. INTRODUCTION

Antenna-coupled detector collection efficiency captures the concept of power output/input and is made up of several sub-efficiencies. In the ideal case all of the available, incident power is collected and transferred to the load. However, many of the fundamental limits of antennas are based on theory described by the Thevenin or Norton equivalent circuit, predicting that the maximum power that can be absorbed by the antenna is only 50% of the total power [1]. And many antennas scatter more power than they absorb, with the minimum scattering antenna exhibiting equal absorbed and scattered powers [2]. Although the fundamental principles of antenna theory are well established, some theoretical aspects regarding circuit models and predictions of power absorption are still debated and questioned [3]-[6]. It also has been shown that the absorption efficiency, which is usually defined as the ratio of the absorbed power by the load and the sum of the absorbed power, and scattered power from antenna in low frequency, could reach more than 50% [7], [8]. In the sub-millimeter and THz spectrum material loss can become prohibitive to antenna collection efficiency, and accounting for the absorption properties is critical to overcoming these limitations. It should be noted that antenna scattering can be divided into two parts: one is called antenna mode scattering, due to the load mismatch to the input impedance of the antenna, but it has the same pattern as the transmitting antenna; another part is called the structural scattering, that can be understood as a receiving current induced on the structure which gives rise to a scattered field. In other words, there is always some scattering power that can be observed from a receiving antenna even with a conjugate-matched load.

We note that the classical minimum scattering antenna follows from a simple analysis that the absorption efficiency is 50% for conjugate matching, which means the amount of power absorbed is same as the power scattered. And it has identical transmitting and receiving pattern, while radiating the same fields in the forward and backward directions. But the most important condition is the minimum scattering antenna is "invisible" when its terminals are open circuited [2]. The half-wave dipole belongs to the minimum scattering antenna category, since it consists of two collinear quarter-

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wave dipoles when open-circuited, and the quarter-wave dipole is poor scatterer, nearly “invisible” [9]. However, the full-wave dipole, when its terminals are open circuited, has two identical half-wave current distribution along the dipole arms and generates a strong scattered field. In this paper, we demonstrate that there can be a significant improvement of absorption efficiencies for the full-wave dipole antenna, comparing to the half-wave dipole.

Recently, one paper has been published to give an extensive analysis of the radiation properties of the full-wave dipole antenna [10]. It is shown that in contrast to a regular RF transmitting antenna which is usually operated at the short-circuit resonance, for the optical antenna the peak of radiated efficiency is located near the open-circuit resonance. Our approach is to investigate the absorption efficiency for the dipole antenna at the open-circuit resonance while achieving matched impedance conditions via a tunable-impedance load, and a circuit model is proposed to give insight into the physical interpretation of a full-wave dipole which is consistent with the ability to achieve greater than 50% of the available power.

2. IMPEDANCE FOR FULL-WAVE DIPOLE ANTENNAS

The dipole antennas have been simulated as 110 nm thick gold structure in free space by using Ansys HFSS, which is based on the finite element method. The full-wave dipoles are designed to operate in the long-wave infrared (LWIR) spectrum. The short-circuit resonances are at 18.5 THz, while the open-circuit resonances are at 28.3 THz with the length of dipole 7.01 um. Figure 1 gives the geometry of the free space dipole. Feeding the infrared dipole antenna at its center feed gap allows one to determine the input impedance, radiation power, reflection efficiency, and Ohmic loss. In Figure 2, the radiation resistance and Ohmic resistance for the full-wave dipole antenna have been plotted. Note that the peak of radiation resistance is located at the open-circuit resonance, consistent with reference [10].

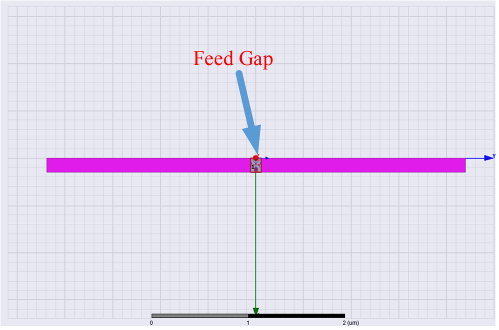

Figure 1. Geometry of a dipole antenna, with excitation port in the feed gap.

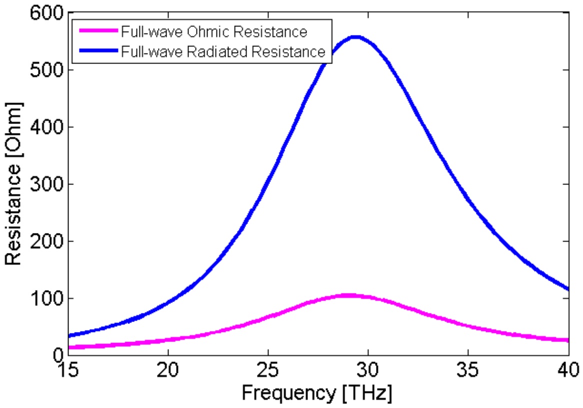

Figure 2. Radiation resistance and Ohmic resistance for the full-wave dipole antenna.

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3. EQUIVALENT CIRCUIT FOR THE FULL-WAVE DIPOLE ANTENNA

The Thevenin, or Norton, equivalent circuit can be used to model the transmitting and receiving antenna [1]. When these models are applied to calculate the absorption efficiency for the receiving antenna, using either a constant voltage source or a constant current generator, it leads to the conclusion that the maximum absorption efficiency is 50% when the load is conjugate matched to the input impedance of the antenna. Here we define the absorption efficiency for the dipole antenna as:

$$\varepsilon = \frac{\mathrm{P(load)}}{\mathrm{P(load)+P(scatter)+P(ohmicloss)}} \tag{1}$$

where P(load) is power absorbed in the matched load, P(scatter) is the power scattered from the antenna, and P(ohmicloss) is the power dissipated due to the metal loss. However, there is an extreme case that when the load is open (impedance of the load goes to infinity) there is zero current in the equivalent circuit and zero scattered power from the antenna. This is true for small dipoles and loops. The concept can be extended to the half-wave dipole antenna since the half-wave dipole antenna consists of two quarter-wave dipoles, when open circuited, and the quarter-wave dipole is a very poor scatterer. But when a full-wave dipole antenna is considered the traditional equivalent circuit breaks down because, for this special case, the full-wave dipole antenna consists of two half-wave dipoles, generating strong scattered field.

Here we propose the equivalent circuit for the full-wave dipole antenna shown in Figure 3. It is evident that we are neglecting the imaginary parts of the load and the antenna impedances because here we consider a resonant full-wave dipole antenna. The circuit model can easily be extended to include the complex impedance of the load with conjugate matching to the antenna, but here we are interested in resonant antenna performance.

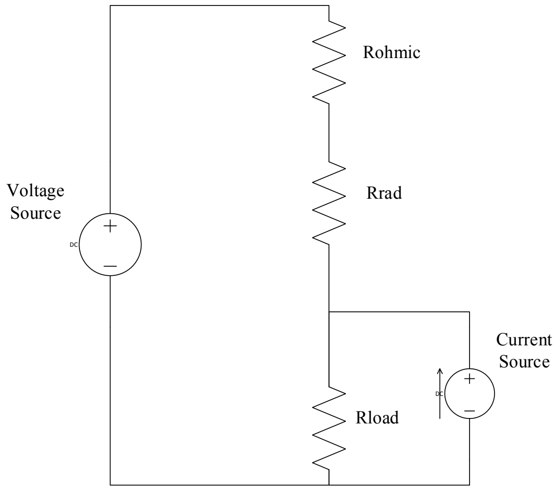

Figure 3. Full-wave dipole equivalent circuit.

In contrast to the Thevenin equivalent circuit, the full-wave dipole equivalent circuit we proposed here has two sources; a voltage source and a current source. However, the load is still in series with the antenna, which is same as the Thevenin equivalent. This full-wave equivalent circuit can be analyzed by applying the superposition principle, as shown in Figure 4, which helps to break down the complex circuit into two simpler circuits each containing one source. The total output is the algebraic sum of the individual outputs from each independent source. It may be noticed that the full-wave dipole equivalent circuit takes into account when the dipole antenna is open circuited. Meanwhile, if the current flowing through the resistance of the antenna (Rohmic+Rrad) generated from the voltage source can be canceled from the current in the antenna produced by the current source, the load will absorb all the power from the sources.

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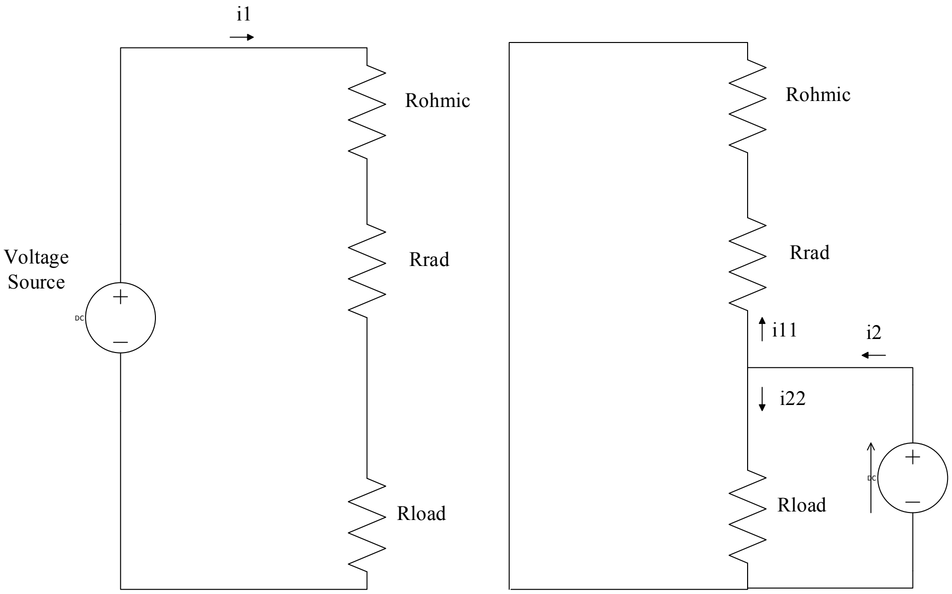

Figure 4. Equivalent circuits with one individual voltage and one individual current source.

4. CIRCUIT EQUATIONS

Circuit equations based on the model described above predict that when the impedance of the load is matched to the impedance of the antenna then maximum power transfer is achieved, which gives the maximum absorption efficiency in the circuit. It is assumed that the voltage and current sources are both real quantities, and they are entirely independent of the load impedance Rload. Solving for the currents i1 and i22, and then calculating the total absorbed power in the load gives:

$$\mathrm{i1} = \frac{\mathrm{V}}{\mathrm{R(ohmic)+R(rad)+R(load)}} \tag{2}$$

$$\mathrm{i22} = \frac{\mathrm{R(ohmic)+R(rad)}}{\mathrm{R(ohmic)+R(rad)+R(load)}} * \mathrm{i2} \tag{3}$$

$$\mathrm{P(load)} = \mathrm{R(load)} * (\mathrm{i1}+\mathrm{i22})^2 \tag{4}$$

where P(load) is the power absorbed in the load. To find the optimum value corresponding to maximum/minimum power transfer to the load, we differentiate Eq. (4) with respect to R(load) and solve for the value of R(load) for which:

$$\frac{\mathrm{dP(load)}}{\mathrm{dR(load)}} = 0 \tag{5}$$

After solving the equations above, we can get R(load)=R(rad)+R(ohmic),when the derivative of P(load) with respect to R(load) is zero. Then the second derivative of P(load) with respect to R(load) needs to be solved to see if it is maximum power absorbed in the load, when R(load)=R(rad)+R(ohmic) :

$$\frac{\partial^2 \mathrm{P(load)}}{\partial \mathrm{R(Load)}^2} < 0 \tag{6}$$

This gives -2*(R(rad)+R(ohmic)) < 0 which always holds since the resistance of the full-wave dipole antenna is always bigger than zero. Therefore, maximum power transfer occurs when the load resistance equals the antenna resistance, which is the sum of the Ohmic resistance and the radiation resistance of the antenna. As discussed before, the voltage

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and current sources are independent of the load impedance, which implies that the total power should be independent of the load impedance, and since the full-wave dipole antenna is operating at the same frequency, the total power should be constant relative to the load impedance. Then we have another relation:

$$\frac{\partial \mathrm{P(ToT)}}{\partial \mathrm{R(load)}} = 0 \qquad (7)$$

where P(ToT) is the total power in the circuit. Here we need to mention that the total power defined here is only the power circulating in the equivalent circuit, it is not the power effectively extracted by the full-wave antenna in its physical operation. Solving the Eq. (7), we can get:

$$\mathrm{V} = \big(\mathrm{R(ohmic)} + \mathrm{R(rad)}\big) * \mathrm{i2} \qquad (8)$$

The absorption efficiency can be calculated from Eq. (1) after substituting Eq. (8), giving:

$$\varepsilon = \frac{4*\mathrm{R(load)}*(\mathrm{R(rad)}+\mathrm{R(ohmic)})}{(\mathrm{R(rad)}+\mathrm{R(ohmic)}+\mathrm{R(load)})^2} \qquad (9)$$

It is interesting to notice that when R(load)=R(rad)+R(ohmic), the absorption efficiency $\varepsilon = 1$. It is necessary to emphasize again that the total power by adding the power from the each elements is just the power circulating in the circuit.

5. SIMULATION FULL-WAVE DIPOLE ANTENNA WITH A MATCHED LOAD

Figure 5 gives the configuration of a full-wave dipole antenna connected to a Ni stub microbolometer load. The impedance of the Ni stub microbolometer can be tuned to match the input impedance of the dipole antenna. Note that the full-wave dipole antenna is designed to be resonant at 28.3 THz, with width 150 nm and thickness 110 nm. The whole structure is illuminated by a Gaussian beam with electric-field strength of 1 V/m polarized parallel to the axis of the dipole.

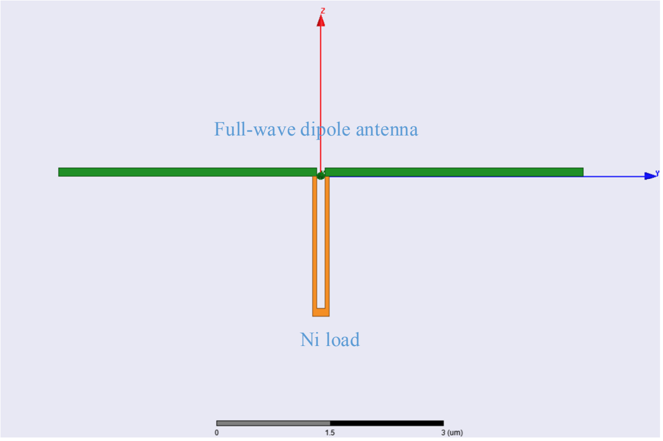

Figure 5. Full-wave dipole with a tunable matched Ni load.

One example is given for the full-wave dipole antenna with a matched Ni load simulated by HFSS. The load resistance equals 500 Ω at 28.3 THz, while the radiation resistance and the Ohmic resistance of the full-wave dipole antenna seen in Figure 2 are 521 Ω and 113 Ω, respectively. The power absorbed by the Ni load, total scattered power and dissipative loss in the antenna are computed. The absorption efficiency can be calculated from Eq. (1), giving $\varepsilon = 68\%$, and it is worth mentioning that the absorbed power is three times bigger than total power scattered from the antenna (P(load)>P(scatter)), consistent with our circuit prediction that absorption can exceed the 50% limit predicted by commonly used models. The absorption efficiency can also be estimated by using Eq. (9), which also predicts greater

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than 50% absorption efficiency. However, the value is bigger than the simulation result, attributed to the fact that the total power circulating in the circuit is smaller than the total captured by the antenna in its physical operation. This missing power is attributed to the additional structural scattering with a matched load and the limitation of using equivalent circuit to calculate the total scattering power from the radiation resistance of the antenna [8], [11].

6. CONCLUSION

The absorption efficiency of full-wave dipole antenna coupled to a Ni stub microbolometer load has been investigated numerically and theoretically. A novel equivalent circuit model is proposed to give insight into the physical interpretation of a full-wave dipole, which predicts the 100% absorption efficiency with a matched load, with the condition that the current flowing through the antenna resistance is canceled by the voltage source and the current source. This ideal case is achievable when material losses are negligible, a condition that diminishes as applications move to higher frequencies across the sub-millimeter and THz spectrum. An example is given to show that with impedance matching to the full-wave dipole antenna at 10.6 μm, the maximum absorption efficiency can be achieved around 68%, which is a significant improvement from 50% efficiency for the minimum scattering antenna, and tremendous improvement over designs in which matched conditions are not achieved. However, deviation between absorption efficiency predicted by full-wave simulation and the equivalent circuit model is noted and attributed to the absence of power associated with structural scattering in the circuit model. The ability to collect greater than 50% of available power in a matched load is consistent with both the simulation and circuit model.

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