

Reception efficiency, resonant lengths and resonant input resistances of an infrared dipole antenna

MOHAMED ABDEL-RAHMAN, ANDIE KUSUMA

Prince Sultan Advanced Technologies Research Institute, College of Engineering, King Saud University, Riyadh, Saudi Arabia 11421

In this letter, we quantify, for the first time, the reception efficiency (RE) of an infrared (IR) dipole antenna. In addition, we study the dependences of the resonant lengths and the resonant input resistances of an IR dipole antenna on the antenna arm width and feed gap separation.

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1. Introduction

The infrared (IR) antenna-coupled sensor technology is a promising detector technology that possesses the potential of providing an uncooled, fast response, inherently frequency agile and polarisation sensitive detector. In antenna-coupled sensors, the radiation-collection and radiation-sensing functions are separate, where an antenna, of a size comparable to the wavelength, λ , of operation, serves to collect and deliver the radiation to a sensor. The sensor's size is much smaller than the wavelength of operation and it is expected to have fast response due to its small size. Commonly employed sensors are microbolometers and metal-insulator-metal (MIM) diodes. A bolometer is a thermal resistor; IR radiation delivered to the bolometer by an antenna will cause a temperature change that will prompt a resistance change which could be read by an electronic circuit. An MIM diode will rectify the radiation delivered by the antenna into a direct current (dc) voltage component that also can be read by an electronic circuit. An example of an antenna-coupled sensor, from [1], is shown in Fig. 1.

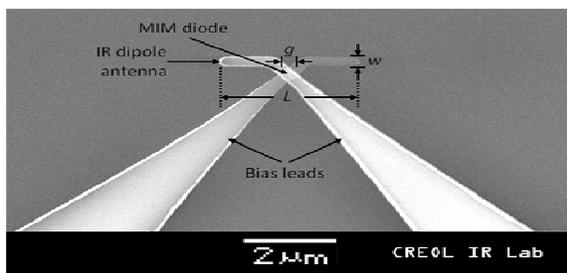


Fig. 1. An electron micrograph of an IR dipole antenna coupled to an MIM diode. From [1].

The performance of antenna-coupled sensors [1-4] is still about three orders of magnitude away from the commercialization limit of IR detectors. Being able to separately measure and analyze the radiation-collection

function is essential in giving directions for future works and thus improving this detector technology; however, an antenna-coupled sensor is a complex detector configuration where it is not possible to separately measure the radiation-collection function. In this letter, we will simulate a typical IR dipole antenna system and provide a detailed quantitative analysis for the radiation-collection function, which is in essence the reception efficiency (RE), of the IR dipole antenna. Moreover, the resonant lengths and the resonant input resistances of IR dipole antenna structures have not been thoroughly studied yet; resonant input resistance data is essential for designing a sensor that is impedance matched to the antenna and thus insuring that all the power collected by the antenna is delivered to the sensor. For, we will study the resonant lengths and resonant input resistances of an IR dipole antenna as a function of the antenna arm width and the antenna feed gap separation, and we will provide design curves that may direct the IR dipole antenna designer for more efficient designs.

2. Reception efficiency of IR dipole antennas

The RE of an IR dipole antenna is affected by four factors. First, the conduction losses in the antenna metallic arms; these losses are expected to be very pronounced for IR dipole antennas as metals are usually very lossy at THz frequencies. The conductivity of a 100 nm thick gold (Au), typical material for IR antenna metallic arms, film is 2.8×10^6 S/m at 28.3 THz (the frequency of interest in this study) as measured in [5], a value that when compared to the low frequency conductivity value for Au, $\sim 4.9 \times 10^7$ S/m, would indicate that high conduction losses are expected at THz frequencies. Second, dielectric losses due to dielectric heating, and they are directly proportional to the loss tangent of the underlying substrate. IR antennas are usually fabricated on Silicon (Si) substrates with silicon dioxide (SiO_2) insulating films. SiO_2 is required for electrical isolation in case of using an MIM sensor and for

both electrical and thermal isolation in case of using a microbolometer. The permittivity of Si at 28.3 THz is $11.7 + j 1.52 \times 10^{-5}$ [6] while SiO₂ has a permittivity of $4.84 + j 0.097$ at 28.3 THz, which implies that some power is expected to be lost as heat in the SiO₂ film. The third factor influencing the RE of the antenna is the power coupled into surface waves in an underlying substrate, this power loss is negligible for thin substrates where a thin substrate is defined to have a thickness of $< \lambda_d/100$, where $\lambda_d = \lambda/\epsilon_r^{1/2}$, whereas, as the substrate gets thicker than $\lambda_d/100$, the efficiency of the antenna decreases as it couples more power to the substrate in the form of surface waves. This power lost to surface waves can be eliminated if the underlying substrate thickness is made infinite; however, in this case, a dipole antenna is expected to couple (receive) only $\epsilon_{air}^{3/2} / \epsilon_{substrate}^{3/2}$ of the power incident on it [7], so power coupling to the substrate is the fourth factor that affects the RE of an IR dipole antenna.

3. Reception efficiency simulations

First, a 0.475λ long ($L = 5.035 \mu\text{m}$) infinitesimal dipole with antenna arms' width (w) and arm thickness (t) of 30 nm and a feed gap separation (g) of 40 nm was simulated in a vacuum surrounding; where L , w , and g are identified in Fig. 1, and t is the thickness of the deposited antenna metal. The conductivity of the antenna arms was set to 1×10^{18} S/m, almost a lossless conductor. This simulation was used to validate the use of the software package, IE3D [8], at such high frequencies as its results can be compared to the classical antenna theory. The simulation resulted in a reception efficiency of 99.95 % and an antenna input impedance of $72 + j 0 \Omega$ at 28.3 THz ($10.6 \mu\text{m}$), which presents a good match with the classical theory. Second, a $2.25 \mu\text{m}$ long antenna with an antenna arm width of 200 nm, an arm thickness of 100 nm, and a feed gap separation of 50 nm lying on 200 nm of SiO₂ and 380 μm of Si was simulated. The material constants that were presented in the previous section are the ones that were used in these simulations. This antenna system is a lossy conductor / lossy dielectric system with a thick substrate. So, conductor and dielectric heating losses as well as losses due to power coupling to the thick substrate ($\sim 120 \lambda_d$) are expected, while power coupling to surface waves is unlikely. The RE of this simulated IR dipole antenna system was found to be 9.11 %, which means that 90.89 % of the power incident on an antenna-coupled sensor is not collected. To further analyze, a third simulation was performed where the previous simulation was repeated using antenna metallic arms having a conductivity of 1×10^{18} S/m; this system is now a lossless (approximately) conductor / lossy dielectric system with an infinite substrate. So, dielectric heating and losses due to power coupling to the thick substrate are expected while

conductive losses will be very minimal and power coupling to surface waves is unlikely. Since we expected the antenna resonant length to change as the conductivity value is altered; accordingly, we rescaled the antenna length in this simulation to resonate at 28.3 THz; the resonant length of the antenna in this simulation was found to be 2.65 μm . The RE of the IR dipole antenna in this third simulation was found to be 14.76 %, from which we can deduce that the conductive losses are responsible for 5.65 % of the received power losses. Conductive losses may be minimized by alloying metals to achieve high conductivities; a dynamic conductivity study [5] of Gold-Copper (Au-Cu) metal alloy with various decompositions showed that the conductivity of a 100 nm Au film can be increased by a factor of ~ 1.78 by using an Au₇₅Cu₂₅ alloy. Different alloys should be further studied targeting higher conductivities. Fourthly, the previous system was simulated with a lossless dielectric (i.e., we removed the complex part of the permittivity of Si and SiO₂). This fourth simulation represents a lossless (approximately) conductor / lossless dielectric antenna system with an infinite substrate. So, power coupling to the substrate and minute conductive losses are expected while power losses in dielectric heating and power coupling to surface waves are unlikely. The RE was found to be 14.82 %, from which we can deduce that the dielectric losses are responsible for only 0.06 % of the received power losses. And finally we simulated the system using antenna arms having a metallic conductivity of 1×10^{18} S/m in a vacuum surrounding. The antenna length was properly rescaled to 9.6 μm in order compensate for the effective dielectric constant (~ 3.56) of the underlying substrate that was present in the previous simulations. This final simulation aids to determine the losses due to power coupling to the dielectric substrate. The RE of this antenna system was found to be 99.92 %, showing that losses due to power being coupled to the underlying dielectric substrate present a substantial 85.1 % of the total antenna losses. The remaining 0.08 % would be referred again to the metallic conduction losses due to the fact that the metal composing the antenna arms is not a perfect conductor; so conduction losses are responsible for $5.65 \% + 0.08 \% = 5.73 \%$ of the total antenna losses. Power coupling to the substrate can be reduced by having an underlying substrate of a low dielectric constant such as silica aerogel. It can be also improved if the substrate was made thinner than $\lambda_d/100$ which will require the development of air-suspended ultrathin insulating films above ground planes. A substrate thickness that is of odd multiples of $\lambda_d/4$ can also eliminate power coupling to underlying substrate and will provide minimal power coupling to surface waves but this will involve having a ground plane which will, in turn, require via holes because the detector has to be connected to the read-out integrated circuit (ROIC). The results of the RE simulations are summarized in Table 1.

Table 1. Reception efficiencies of an IR dipole antenna simulated at different conditions.

Simulated Antenna system	Lossy conductor/Lossy dielectric	Lossless (approx.) conductor/Lossy dielectric	Lossless (approx.) conductor /Lossless dielectric	Lossless (approx.) conductor /Vacuum
Reception efficiency (%)	9.11	14.76	14.82	99.92

4. Antenna arm width and feed gap separation study

In this study, we evaluated the effect of antenna arm width and feed gap separation on the resonant length and resonant input resistance of the antenna. For, we simulated an IR dipole antenna with an arm thickness of 100 nm, lying on 200 nm of SiO₂ and 380 μm of Si. The arm width was varied from 100 to 250 nm in increments of 50 nm, while the feed gap separation was varied from 50 to 300 nm in increments of 50 nm. The resonant lengths and the resonant input resistances were determined at different cases. The simulation results are plotted in Fig. 2 through Fig. 5. From these figures we can observe that for the IR dipole antenna dimensions that we simulated, the resonant length varies between 2.14 to 2.91 μm whilst the antenna resonant resistance varies from 92.2 to 210 Ω depending on both the arm width and the feed gap separation of the given antenna structure. It was noted, that the resonant length and the resonant input resistance are inversely proportional to the width of the antenna arm and directly proportional to the feed gap separation. By extrapolating the curve in fig. 4 for $w = 200$ nm, we found that the resonant length for an IR dipole antenna with a feed gap separation of 400 nm is 3.085 μm. This finding is in excellent agreement with the measured result in [9], where an identical IR dipole antenna (having $g = 400$ nm, $w = 200$ nm, $t = 100$ nm lying on 200 nm of SiO₂ and 380 μm of Si) was found to have a resonant length of 3.1 μm at 28.3 THz. Furthermore, we have found that the IR dipole antenna stops resonating at an arm width of 300 nm where the antenna input impedance tends to be capacitive.

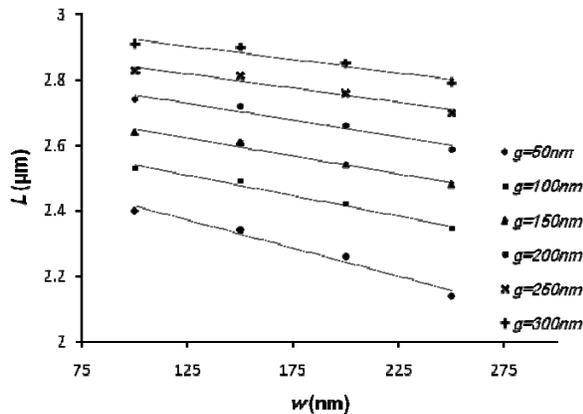


Fig. 2. Antenna resonant length (L) versus antenna arm width (w) at various antenna feed gap separations (g).

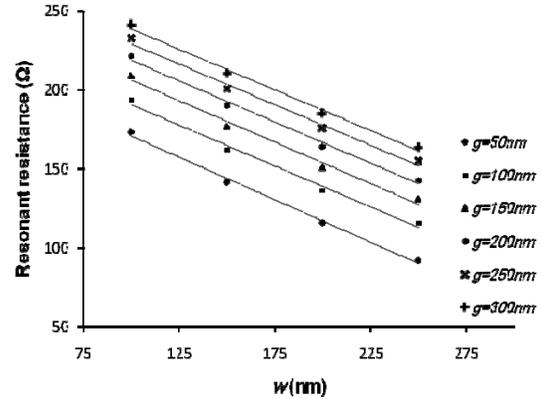


Fig. 3. Antenna resonant input resistance versus antenna arm width (w) at various antenna feed gap separations (g).

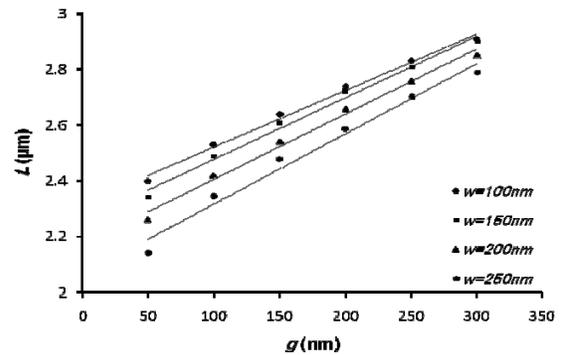


Fig. 4. Antenna resonant length (L) versus antenna feed gap separation (g) at various antenna arm widths (w).

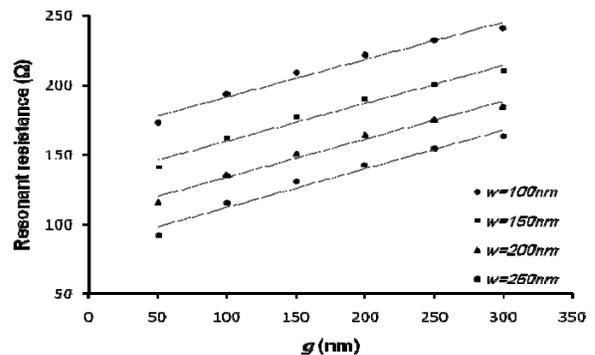


Fig. 5. Antenna resonant input resistance versus antenna feed gap separation (g) at various antenna arm widths (w).

5. Summary

We discussed and quantitatively analyzed the RE of a typical IR dipole antenna system. It was found that 90.89 % of the power incident on a dipole antenna-coupled sensor is not collected, primarily due to power being coupled to the underlying substrate and secondarily due to metallic conduction losses. Furthermore, we have provided design curves for a typical IR dipole antenna system. Using these design curves, one can choose the proper dimensions to design an IR dipole antenna that is impedance matched to the accompanying sensor.

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*Corresponding author: mabdelrahman@ksu.edu.sa