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# The effect of metal dispersion on the resonance of antennas at infrared frequencies

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ABSTRACT

In this paper the optical parameters at infrared frequencies of metallic thin films were obtained experimentally using a variable angle spectroscopic ellipsometer and used to simulate numerically the frequency response of antennas and antenna-coupled detectors at infrared frequencies (5–15 μm). The simulation results agree with previously published data and practical guidelines are presented for the design and fabrication of dipole and bowtie antennas at infrared frequencies.



## 1. Introduction

The design and optimization of radiofrequency (RF) antennas is in a very mature stage compared to their higher frequency counterparts, this is mainly due to the use of high performance computer aided design (CAD) software initially developed for the radar and communication design industry [1].

Recently a great deal of interest has been placed in designing and fabricating antennas at optical and infrared frequencies which would have a positive impact on size, bandwidth, responsivity, and are capable of dual-band detection [2,3]. These optical and infrared antennas have potential applications in diverse areas such as optical sensors, lasers and high-resolution microscopy and spectroscopy [4].

The fabrication of antennas at optical frequencies demands design rules that would make possible to transfer established antenna designs from microwave and radio frequencies to the optical frequency range [4]. These design rules cannot be obtained with the same formalisms used at longer wavelengths, and need a proper adaptation to include the strong dispersive properties of metals in the IR and visible regions where the dynamic conductivity is not as high as in the microwave range [5].

Recently the concept of "lumped" circuit elements has been introduced in order to design and synthesize filters, transmission lines and antennas at optical frequencies [2,5,6] as it has been routinely done at lower frequencies. However, for the specific task of finding the resonance of a metallic antenna at optical frequencies the use of commercially available 3D electromagnetic simulation software such as HFSS (Ansoft, Pittsburgh, PA), Comsol Multiphysics (Comsol Inc., Burlington, MA) or CST Microwave Studio (CST Inc., Framingham, MA) could be used if the optical parameters for the specific metal are known and included in the calculation [7].

In this contribution we have used the COMSOL Multiphysics software. This software package is based on the finite element method (FEM) which solves systems of coupled three-dimensional partial differential equations. Thus it can be used to model physical phenomena in a wide range of applications including electromagnetics. It can easily model, at a moderate computational cost, complex material properties that cannot readily be modeled with finite-difference-based programs [8].

In this paper the optical parameters at infrared frequencies of metallic thin films were obtained experimentally using a variable angle spectroscopic ellipsometer. The measured data was used to simulate numerically the frequency response of dipoles and bowties at infrared frequencies (5–15 μm).

## 2. Method

In order to obtain the optical parameters at infrared frequencies for gold, aluminum, copper and nickel, 75 nm-thick films of these metals were e-beam evaporated on Si substrates and characterized

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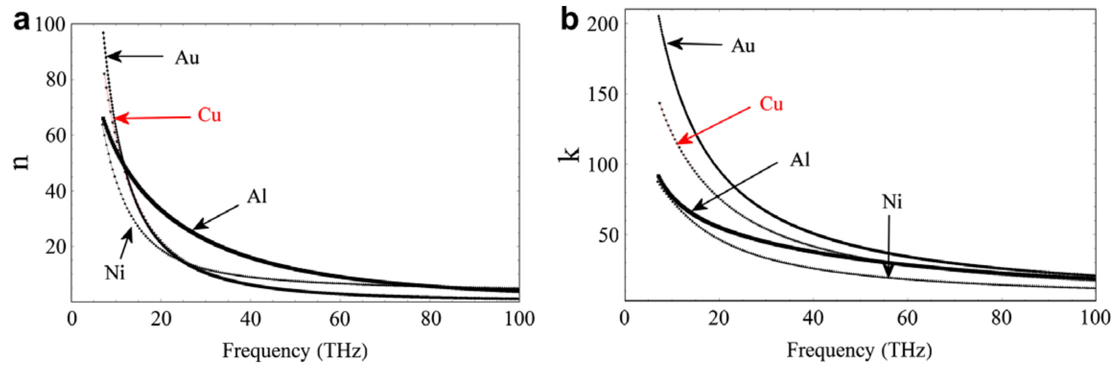


**Fig. 1.** Experimental values of *n* and *k* for gold, aluminum, copper and nickel films as a function of frequency. The solid line represents the fitting of the experimental data to a polynomial of (1/*f*).

on a J.A. Woollam infrared variable angle spectroscopic ellipsometer (IR-VASE). Fig. 1 shows the *n* and *k* values obtained for gold, aluminum, copper and nickel films as a function of frequency.

The values of *n* and *k* obtained experimentally are within 10% of the values previously reported in the literature [9–11], the difference might be due to the deposition technique used and the thickness of the film. The use of measured material parameters in the simulations increases the accuracy of the results and will give a better prediction of the real performance of the fabricated device.

Numerical simulations of metallic dipole and bowtie antennas on air were performed using COMSOL Multiphysics. The dipole antenna had a total length of 4.3 μm, a width of 300 nm and 200 nm of thickness. The bowtie antenna had a flare angle of 60° being the thickness and total length the same as of the dipole. For the dipole, these dimensions give a theoretical resonance around 8.6 μm (34.8 THz). The feedgap of the antennas was 300 nm long and was filled with the same metal used for the antenna to simulate a perfectly matched load [4] or with a different metal to simulate an antenna-coupled microbolometer [12].

The electromagnetic simulation was performed by launching a linearly polarized plane wave with the polarization set to match the polarization of the antenna. The electric-field-amplitude of the plane wave was 1 V/m and the induced current in the antenna as a function of the plane wave's frequency was measured by integrating the surface current density over the antenna cross-section at its geometrical center. Matched boundary conditions were used in the FEM simulations and tetrahedral elements were used to discretize the computational domain. The frequency-dependent *n* and *k* values which were previously measured for each metal were used as the material parameters for the simulation. In order to speed up the algorithm, the experimental data was fitted to a polynomial expansion in terms of (1/*f*). Fig. 1 shows the experimental data and the solid line obtained from the fitting polynomial function.

## 3. Results

Perfectly matched dipole antennas (metallic rods) were simulated and the induced current as a function of frequency was obtained. Fig. 2 shows the response of gold, aluminum and copper dipoles as a function of frequency from 20 to 60 THz (15–5 μm) compared to the theoretical resonance at 34.8 THz (8.6 μm). It can be seen from Fig. 2 that there is a resonance shift from 34.8 to 29.8 THz for gold, 29.5 THz for copper and 29.7 for aluminum (10.06 μm, 10.16 μm and 10.10 μm, respectively), which agrees with studies that show that resonant antennas at optical frequencies are shorter than one half the wavelength of the incident light [4]. The resonant shift shown in Fig. 2 is around 15% off the $\lambda/2$ resonance, which agrees with experiments at infrared frequencies

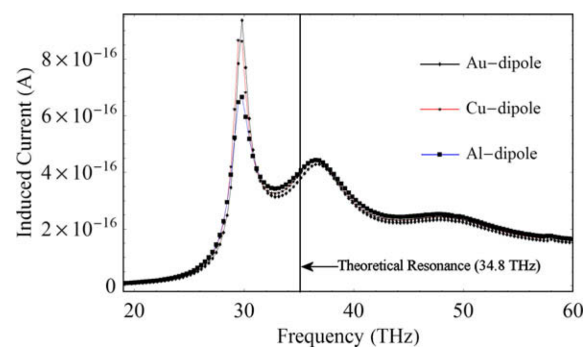


**Fig. 2.** Current induced by a linearly polarized plane wave on gold, aluminum and copper dipoles as a function of frequency.

where antennas turned out to be around 20% shorter than the value predicted by antenna theory [13,14].

It is also worth noting that the selection of gold, aluminum and copper does not make a significant impact on the resonant frequency of dipoles at far-infrared frequencies, contrary to what has been reported at visible frequencies where an aluminum dipole resonates at half the wavelength of a gold dipole with the same length [5]. The selection of metals does affect however the magnitude response of dipoles at infrared frequencies, from Fig. 2 it can be seen how an aluminum dipole has a 30% lower response than a gold dipole, which has also been reported for aluminum and gold dipoles at visible frequencies [4].

In order to find out the influence of the dispersive characteristics of *n* and *k* simulations were performed using constant values for *n* and *k* and using only the real part of the index of refraction. Fig. 3 shows the simulation of gold dipoles using the frequency-dependent *n* and *k* values compared to using only the value of *n* and *k* at the theoretical resonant frequency given by classical antenna theory (34.8 THz), it also shows the dipole's response when the material is characterized by only the real part of the index of refraction.

The frequency response of the antenna does not change significantly by using the material parameters at a fixed value close to the resonance compared to using the frequency-dependent values for *n* and *k*. Both curves intersect at 34.8 THz where the material parameters are equal and then the response deviates as we move away from that frequency. However the simulations performed with only the real part of the index of refraction gives lower values of induced current and a resonance at 33.2 THz which is closer to the theoretical resonance predicted by classical antenna theory (34.8 THz). This calculation shows that for antennas at infrared frequencies there is no advantage in including the dispersive proper-

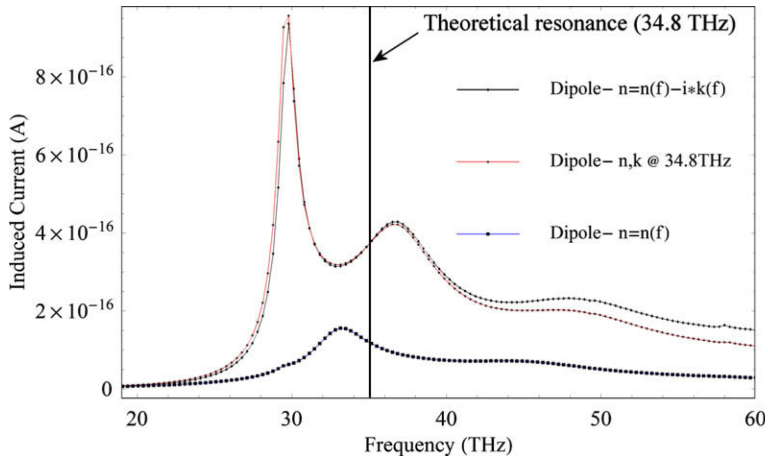


**Fig. 3.** Simulation of gold dipoles using frequency-dependent *n* and *k* values compared to using only the value of *n* and *k* at the theoretical resonance frequency given by classical antenna theory (34.8 THz) and the response of a gold dipole characterized by only the real part of the index of refraction.

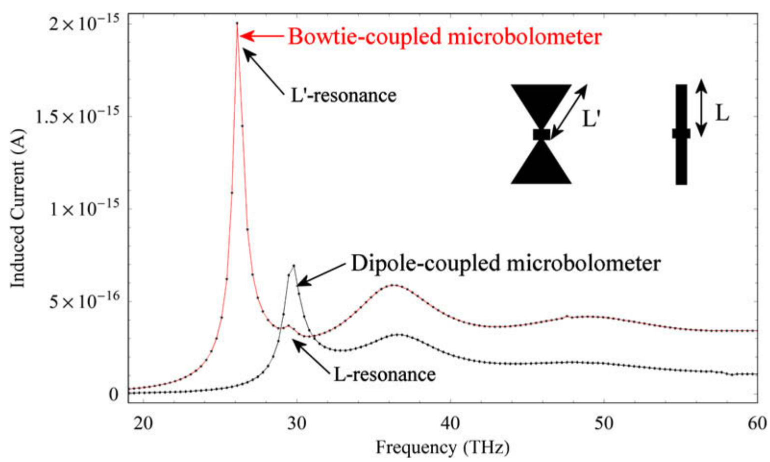


**Fig. 4.** Numerical simulation of a dipole-coupled microbolometer and a bowtie-coupled microbolometer made of gold with a nickel bolometer at the feed.

ties of the materials as long as the complex part of the index of refraction is included ($k$).

Fig. 4 shows the response of a dipole and a bowtie-coupled microbolometer, the antenna arms are made of gold, and the bolometer is a 200 nm thick, 300 nm wide and 300 nm long nickel microbolometer, the bowtie had a 60° flare angle. The simulations were performed using the frequency-dependent values of $n$ and $k$ obtained experimentally (Fig. 1). For the same input electric field, the bowtie-coupled microbolometer (Fig. 4) showed a response approximately 3 times higher than the dipole and a resonance at a lower frequency (26.1 THz). The higher response is due to the larger collection area in comparison with the dipole and the 13% decrease in resonant frequency is consistent with the 15% increase in length due to the 60° flare angle.

When comparing the results obtained for the dipole with a perfectly matched material, and the simulation made with a coupled microbolometer (Figs. 2 and 4) we can see that coupling a piece of a different metal at the feed of an antenna does not influence its resonant frequency, it does however decrease the response of the antenna due to the impedance mismatch between the antenna and the load.

## 4. Discussion

Classical antenna theory must be modified to design antennas at infrared frequencies. The effect of current waves propagating along the metal is quite different at optical frequencies from those arising at microwave and lower frequencies. Therefore, the actual values of the material parameters for the metals at those frequencies have to be available in order to make an accurate antenna design.

From the numerical results obtained in the simulations performed in this paper we propose the following design rules that link classical antenna theory with antennas at infrared frequencies:

(a) The length of a resonant dipole antenna at infrared frequencies will be 15–20% shorter than the theoretical $\lambda/2$ resonant length. This resonant length does not change significantly when selecting gold, aluminum or copper to fabricate the dipole.
(b) Numerical simulations of metallic antennas can be done by using the material parameters at a single frequency with acceptable results at frequencies around that central frequency as long as the complex part of the index of refraction is included.
(c) No resonance shift was observed by placing a bolometric detector at the antenna feed. Only a decrease in response due to the impedance mismatch was observed.
(d) Bowtie antennas resonate at a lower frequency than dipole antennas of the same length, the resonant frequency for the bowtie antenna can be estimated as $L/\cos(\alpha/2)$, being $\alpha$ the flare angle of the bowtie (Fig. 4).

These design rules can be a useful aid in the fabrication of antennas and antenna-coupled detectors at infrared frequencies.

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