Response Increase of IR Antenna-Coupled Thermocouple Using Impedance Matching

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***Abstract*—The response of a bowtie antenna-coupled thermocouple operating at 10.6 μm is studied for varying lengths of a transmission line, which connects the antenna to the thermocouple and functions as an impedance-matching element. Peaks in the response are observed for several lengths of transmission line. Most notably, the response of a device with a transmission line length of 1.3 μm is increased 2.4 fold when compared to the device without the transmission line. The analytical response of a microwave circuit describing the detector is in agreement with the measurements, indicating that the increases in the response are caused by an improved impedance match between the antenna and thermocouple facilitated by the transmission line. This experiment demonstrates for the first time impedance matching principles applied to infrared antenna-coupled thermal detectors.**

***Index Terms*—Antennas, impedance matching, infrared detector, thin-film devices.**

I. Introduction

Antenna-coupled thermal sensors offer a unique choice for infrared detection applications. The antenna, which captures the incident radiation, can be designed to meet directional, polarization, and spectral requirements [1]–[3]. The sensing element, most often a bolometer, is located at the feed-point of the antenna. The sub-micrometer size and therefore small thermal volume of the sensing element enables a fast response time [4], [5]. Planar antenna designs are common, since they are straightforward to fabricate and mechanically robust. The drawback of antenna-coupled thermal sensors is their relatively poor sensitivity with typical specific detectivity (D*) values of $\sim 10^5$ cm Hz$^{1/2}$/W [6] compared to D* values reaching the low 10^9 cm Hz$^{1/2}$/W for thermally isolated and larger sized thermal detectors without antennas [7], [8]. Only more elaborate fabrication methods to improve the thermal isolation of antenna-coupled bolometers have yielded significant response increases, $D* = 1\times10^8$ cm Hz$^{1/2}$/W [6].

A microwave engineering concept is used in this paper to increase the response of a planar bowtie antenna-coupled thermocouple. The antenna and thermocouple are each described by their impedances. If these impedances are not matched, a portion of the antenna currents, which are induced by the incident infrared radiation and cause the response of the device, are reflected by the thermocouple and therefore limit the response. Impedance matching is essential to couple the energy captured by the antenna efficiently to the load as shown in simulations of optical antennas [9], [10].

A transmission line, which functions as an impedance-matching element, is inserted between the antenna and the thermocouple and variations in the magnitude of the response are observed as a function of the transmission line length. Simulations show agreement with the measurements. To explain the origin of the response enhancement, a microwave circuit model describing the planar antenna-coupled thermocouple is used to analytically calculate the response. The length of the transmission line modifies the matching conditions of the antenna and the thermocouple and therefore varies the response of the device. While this model is not a complete description of the signal generating process, it shows a similar trend as the measured data, indicating that the underlying cause for the response increase is an improvement in the impedance match between the antenna and the thermocouple.

II. Detector Operation

An infrared antenna-coupled thermal detector operates by receiving incident infrared radiation that excites currents in the antenna. These currents, which are passing through the thermal detector located at the feed point of the antenna, are dissipated as Joule heating. The resulting increase in temperature is sensed by the thermal detector.

The type of thermal detector commonly used is a micro- or nano-bolometer [2], [11]. In the experiment described, however, a thermocouple is utilized. Unlike a bolometer, the thermocouple is operated without bias. Generally, the thermocouple is formed from two wires, each made of different materials A and B with dissimilar Seebeck coefficients S_A and S_B. The wires are joined together at one end and open-circuited at their other ends. By inducing a temperature difference ΔT between the joined ends and the open ends, an

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open-circuit voltage $V_{OC} = (S_A - S_B)\,\Delta T$ can be measured between the open ends of the wires [12].

In the studied antenna-coupled thermocouple, a gold and a palladium wire form the thermocouple. The thermocouple's hot junction is located where the wires are connected to each other at the antenna, which creates a spatially confined hot spot due to its interaction with the incident irradiance. The other ends of the approximately 25 μm long wires form the thermocouple's cold junction and are attached to 1.3 mm long gold lead-lines, which are connected to bond-pads that are used for reading out the response of the devices.

The incident IR radiation may cause heating of the substrate during the measurement. This and other ambient temperature fluctuations do not contribute to the measured response, since they are experienced equally by the two closely spaced junctions of the thermocouple and are therefore cancel out.

Possible methods for increasing the response of the antenna-coupled thermocouple include decreasing the thermal conductivity of the substrate to allow the detector to heat up more or replacing the materials constituting the thermocouple to maximize their Seebeck coefficients. These, however, are not the only methods to improve the device performance. Without altering the materials used in the construction of the detector, the response can be increased using microwave engineering principles. The antenna and the hot junction of the thermocouple can be described by their impedances, Z_{ANT} and Z_{TC}. If these two impedances are not matched, a portion of the antenna currents will be reflected at the thermocouple, which limits the response of the device. A common microwave engineering approach is to insert a transmission line, which is described by its characteristic impedance Z_0, propagation constant β, and attenuation constant α, between the antenna and thermocouple. The input impedance of the terminated transmission line varies with the line length l [13]

$$Z_{in}(l) = Z_0 \frac{Z_{TC} + Z_0 \tanh(\gamma l)}{Z_0 + Z_{TC} \tanh(\gamma l)}, \quad (1)$$

where $\gamma = \alpha + j\beta$. Ideally, the properties and length of the transmission line are designed so that the input impedance of the transmission line, which is terminated by the thermocouple, is equal to the impedance of the antenna. Consequently, no antenna currents will be reflected at the input of the transmission line, which results in an increased response.

In the outlined experiment, a planar bowtie antenna design was selected, since for the given bow angle a large input impedance of $\sim$200 Ω is expected [14]. Ideally, the bowtie antenna is infinite in length, which results in a frequency independent input impedance. Without affecting the properties of the antenna, its overall length can be truncated to $\sim 2\lambda_0$ [14]. However, to prevent the surrounding lead lines from influencing the antenna, its length was reduced to 5 μm ensuring a separation between the antenna and lead lines of at least 20 μm. Simulations indicated an increase in the input impedance to 285.28 - j20.36 Ω. The hot junction of the thermocouple terminates the transmission line in a short of only a few ohms. This large impedance mismatch suggests that the use of a transmission line should improve the response of the device. Therefore, the response of a bowtie antenna-coupled thermocouple is studied for various lengths of transmission line inserted between the antenna and the thermocouple. The type of transmission line selected for this experiment is a coplanar strip transmission line (CPS), which consists of two parallel metal conductors that are straightforward to integrate with planar antenna layouts [15], [16].

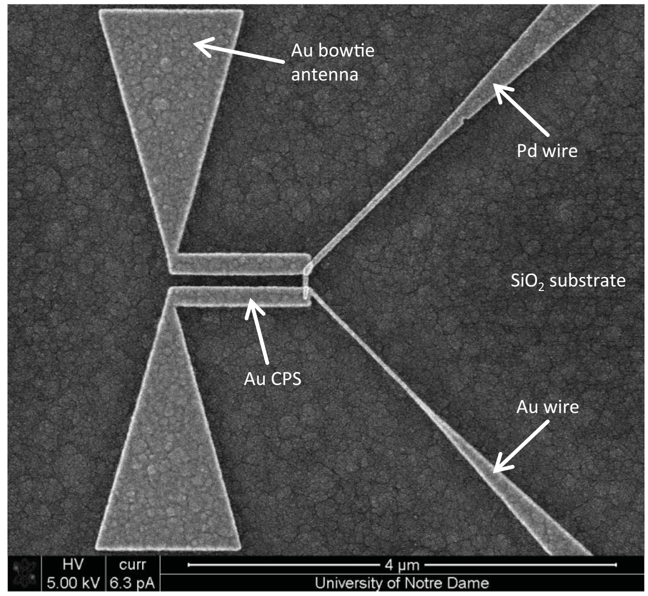

Fig. 1. Scanning electron micrograph of a bowtie antenna-coupled thermocouple with transmission line of length 1.3 μm located on a SiO_2 substrate. The antenna, transmission line, and one wire of the thermocouple are fabricated of gold. The second wire, which connects the end of the CPS, is composed of palladium.

III. Experiment

A. Fabrication

The substrate of the bowtie antenna-coupled thermocouples is prepared by electron-beam evaporation of 50 nm of aluminum onto a silicon wafer to form a ground plane, which is then covered by a 1.3 μm thick layer of SiO_2 using plasma enhanced chemical vapor deposition. The lead lines and bond pads are defined using optical lithography. These features are metallized by a 2 nm thick adhesion layer of titanium and 20 nm thick gold layer using electron beam evaporation. The bowtie antenna, transmission line, and one of the thermocouple wires are patterned using electron-beam lithography and metallized with a 2 nm thick titanium adhesion layer and a 50 nm thick gold layer. In a subsequent electron-beam lithography step, the second thermocouple wire is defined and metallized with a 50 nm thick palladium layer. Lift-off is performed after each of the metallization steps to remove the unnecessary resist and metal.

The overall length of the bowtie antenna is 5 μm with a bow angle of 30°. The two strips of the CPS are each 210 nm wide and are separated by 90 nm. Several devices with CPS lengths of 0, 0.75, 1.3, 2.5, and 4 μm were fabricated. Figure 1 shows a scanning electron micrograph of one of the fabricated devices with a CPS length of 1.3 μm.

The ground plane is separated by a $\lambda/4$ thick standoff layer (1.3 μm of SiO_2), which allows the reflected and incident

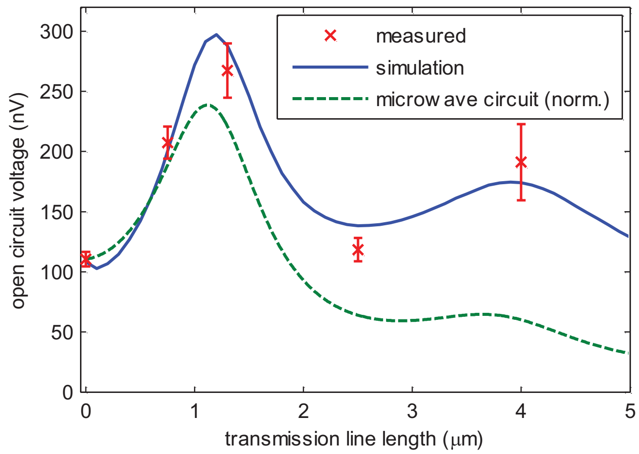

Fig. 2. Comparison of measured device responses, numerical simulation, and response calculation using a microwave circuit representation of the detector (explained in the following analysis section). Each measured data point represents the average of the responses of at least three nominally identical devices with one standard deviation indicated by the error bars.

radiation to add constructively, resulting in an increase of the antenna currents and therefore the response.

Simulations show that the ground plane does not alter the mode on the CPS nor does it create a microstrip mode. The electric field distribution on the CPS remains oriented orthogonal to a microstrip mode whose field lines are directed perpendicular to the ground plane [17]. The transmission line mode most likely remains unaffected by the ground plane, since the distance between the ground plane and the conductors of the CPS is sufficiently large, i.e. it is ~14× larger than the gap between the conductors of the CPS.

B. Measurement

Each of the fabricated devices are characterized by subsequently illuminating them with a CO_2 laser operating at its main emission line of 10.6 μm. The laser is incident onto the device normal to the air/SiO_2 interface. A half wave plate is used to ensure that the linear polarization of the laser beam is parallel to the axis of the bowtie antenna. The device is illuminated with 1.42 W/cm^2 and the open-circuit voltage produced by the thermocouple is measured with a lock-in amplifier, which is synchronized to the frequency of a mechanical chopper that modulates the laser beam.

The responses of the measured devices are shown in Fig 2. Each data point represents the averaged responses of at least three nominally identical devices. The error bar indicates one standard deviation of the measured data set.

Included in Fig 2 are the results of a numerical simulation (using COMSOL) where the increase in the temperature of the thermocouple was computed in response to an incident electric field. Analogous to the measurement setup, the devices in the simulation were illuminated with 1.42 W/cm^2. To allow a direct comparison between the measured responses and the simulated temperature increase, the open-circuit voltage of the simulated devices was calculated with the Seebeck coefficient of $S_{Au-Pd} = 3.0 \pm 0.1$ μV/K, which was measured separately for a gold-palladium thermocouple of similar dimensions and fabricated under similar conditions [18].

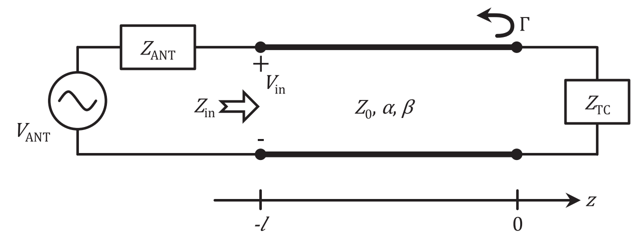

Fig. 3. Microwave circuit representation of antenna-coupled thermocouple. Impedance of the thermocouple is connected with a transmission line of length l to the antenna, which is supplying a voltage that is divided between the impedances of the antenna and the thermocouple.

The simulation predicts the response of the fabricated devices only if the properties describing the materials are accurate. The complex permittivity of the materials used in the fabrication of the devices was measured at 28.3 THz with a J. A. Woollam IR variable-angle spectroscopic ellipsometer (IR-VASE). Their thermal properties were found in [19], which lists properties of only bulk materials. The thermal conductivity values of gold and palladium were reduced by a factor of three to approximate the difference between bulk and thin film materials [20], [21].

IV. Analysis

The numerical simulation shows good agreement with the measured data. Shown in Fig 2, as the CPS length is increased, the response of the device repeatedly increases and decreases. The largest response increase was measured for a device with a transmission line length of 1.3 μm. Its response was increased 2.4 fold when compared to the device without the CPS. For longer transmission line lengths the oscillations in the magnitude of the response are damped by attenuation in the CPS.

Differences between the measured and simulated data may be attributed to the simulation not including the surface roughness of the transmission line, which leads to scattering of propagating surface waves resulting in reduced responses most noticeable for devices with long CPS lengths [15]. A further reason for the differences might be that the approximations made for the thermal conductivities of the gold and palladium thin films were not accurate enough.

The oscillations in the response of the device are caused by the transmission line transforming the impedance of the thermocouple. For certain CPS lengths the transformed impedance matches better the antenna impedance, resulting in a larger response. The impedance matching is worse for other lengths of the transmission line causing a lower response. This concept is best illustrated by calculating the response using a microwave circuit representation [13], shown in Fig 3, of the antenna, CPS, and thermocouple.

The response calculated using this microwave circuit representation of the antenna-coupled thermocouple is the power dissipated in the thermocouple assuming a constant voltage supplied by the antenna. The input impedance of the CPS terminated by the thermocouple is calculated with Eq. 1 and used to determine the voltage at the input of the transmission line. Further, this input voltage can be expressed as a wave propagating towards the thermocouple where it is partially reflected and continues propagating in the opposite direction

$$V_{in} = V_{ANT} \frac{Z_{IN}}{Z_{IN} + Z_{ANT}} = V_o^+ \left[e^{\gamma l} + \Gamma e^{-\gamma l} \right], \quad (2)$$

where $\Gamma = (Z_{TC} - Z_0) / (Z_{TC} + Z_0)$ is the reflection coefficient. Once the magnitude of the forward propagating wave V_o^+ is determined, the voltage across the thermocouple is found

$$V_{TC} = V_o^+ [1 + \Gamma]. \quad (3)$$

Finally, the power delivered to the thermocouple is calculated as

$$P_{TC} = \frac{1}{2} Re \left\{ V_{TC} I_{TC}^* \right\}, \quad (4)$$

where the complex conjugant of the current passing through the thermocouple is defined as $I_{TC}^* = V_{TC}^* / Z_{TC}^*$. This calculation was carried out for several lengths of the transmission line. The resulting power delivered to the load causes a linear increase in temperature [22], which in turn results a linear increase in the output voltage of the thermocouple. Therefore, the calculated power delivered to the thermocouple can be normalized and compared to the measured response, as shown in Fig 2.

The electrical properties characterizing each component used in this calculation were determined by numerical simulations evaluated at 28.3 THz. The input impedance of the antenna is $Z_{ANT} = 285.28 - j20.36\ \Omega$. The CPS has a characteristic impedance of $Z_0 = 125.60 + j11.83\ \Omega$, an attenuation constant of $\alpha = 0.18\ \mu\text{m}^{-1}$, and a propagation constant of $\beta = 1.14$ rad/μm. The impedance of the thermocouple was determined to be $Z_{TC} = 2.47 + j8.88\ \Omega$.

The magnitude of the response predicted by the microwave circuit representation is generally smaller than the measured and simulated values, exhibiting the largest differences for devices with the longest CPS lengths. A possible source for this error might be that the microwave circuit model does not account for the wires of the thermocouple interacting with the incident radiation. During the measurement, these wires couple an additional portion of the radiation to the hot junction of the thermocouple causing an increase in the response. However, the response calculated using the microwave circuit representation of the detector shows the same trend of oscillations in the response as the measured and the simulated data. This indicates that the peaks in the response for CPS lengths of 1.3 and 4 μm are caused by a better energy transfer from the bowtie antenna to the thermocouple due to the improved impedance matching facilitated by the transmission line.

This experiment illustrates that the concept of impedance matching can be applied to infrared antenna-coupled thermal detectors to increase their response. While the 2.4 fold increase in the measured response is promising, it was not enough to increase their $D*$ values past the $\sim 10^5$ cm Hz$^{1/2}$/W range.

Several options can be explored to further increase the response of the detector. By modifying the width and separation of the conductors of the CPS, the characteristic impedance, as well as the propagation and attenuation constants of the transmission line are altered. By designing the characteristic impedance of the CPS, the impedance match between the antenna and thermocouple and therefore the response of the device can be optimized. For example, by using the microwave model of the detector and only varying the characteristic impedance of the transmission line, a 7.2× increase in the response should be possible if $Z_0 = 18\ \Omega$ and the CPS length is 0.9 μm. Further studies are required to determine the dimensions of a transmission line with this characteristic impedance and if it is feasible to fabricate.

Reduction of the losses in the transmission line will also increase the response of the detector. This can be accomplished by decreasing the surface roughness of the gold conductors, which scatters propagating waves. Additionally, the materials surrounding the CPS also contribute to the losses of the transmission line. Currently, the CPS is located on a SiO_2 substrate, which should be replaced by a material exhibiting less losses at infrared frequencies, such as benzocyclobutene [1], [17].

To generate a larger response from the rise in temperature, the metal combination that constitutes the thermocouple should be optimized. Other metals or semiconductors possessing larger Seebeck coefficients should be used in place of the gold-palladium thermocouple.

Lastly, suspending the thermocouple in air or fabricating it on a thin membrane would allow the detector to heat up more and result in a larger response [6], [8].

V. Conclusion

The response of a bowtie antenna-coupled thermocouple to 10.6 μm radiation was investigated. A transmission line was inserted between the antenna and thermocouple and changes in the magnitude of the response were observed as a function of the transmission line length. Numerical simulations showed agreement with the measurements, in particular, peaks in the response for transmission line lengths of 1.3 and 4 μm were observed.

A microwave circuit representation was used to calculate the response of the detector. Agreement with the trend of the measured data indicates that the underlying cause for response increase is an improved impedance match between the antenna and thermocouple, which is facilitated by the transmission line and allows more power to be delivered to the thermocouple.

The measured 2.4 fold increase in response for a device with a transmission line length of 1.3 μm compared to a device without a transmission line showed that impedance matching concepts commonly employed in microwave engineering also apply to infrared antenna-coupled detectors. More drastic increases in the response are expected by modifying the dimensions of the transmission line, which adjusts its characteristic impedance. A properly designed characteristic impedance of the transmission line can optimize the impedance match between the antenna and thermocouple.

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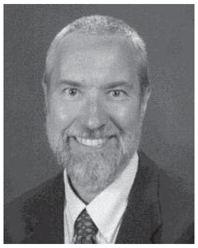

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