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Electrically Driven Terahertz Metamaterial Diffractive Modulator

by

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ABSTRACT

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This thesis describes a method for terahertz (THz) modulation using active metamaterials. At optical and telecom frequencies, modulation of freely propagating and guided signals is an important concept that is fundamental to key technologies and applications such as communications and imaging. At THz frequencies, the ability to modulate these signals at the capacity necessary to effectively realize these applications does not currently exist. In order to remedy this, we investigate the use of metamaterials to modulate free space propagating waves at THz frequencies. Metamaterials are an ideal modulation platform for use in the THz frequency range because they avoid many issues that have challenged traditional THz modulators. Furthermore, the ability of metamaterials to function as artificial media holds considerable potential in the THz frequency range because it allows for a wide range of tunable material parameters extending beyond natural THz material responses. We developed and demonstrated a switchable diffractive modulator using an electrically driven metamaterial to tune transmission in real-time via voltage application. The metamaterial elements are grouped, forming the grating structure. We observed that the device operates as a relatively high-speed, wide-bandwidth, high-contrast modulator, with more than 20 dB of dynamic range.
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Introduction

In this introduction, background information will be provided to give context to the supporting foundation of this experiment.

1.1. Terahertz Band

The terahertz (THz) band of the electro-magnetic (EM) spectrum lies between the infrared and microwave bands. This range of frequencies, spanning 100 GHz to 10 THz, has historically been known as the “terahertz gap” [1]. This gap has been characterized by a difficulty in the development of convenient and efficient methods for generation, detection, and manipulation of terahertz radiation [1]. This difficulty includes the challenge of developing analogs to even the most basic photonic devices that are foundational in other regions of the EM spectrum. A major source of the gap is an absence of convenient and efficient materials that have the needed interactions with THz radiation; this is in contrast to common-place
materials that are fundamental to our understanding of other frequency regions. However, in other ways, the THz region is related to and draws its properties from the neighboring visible and microwave frequency regimes; correspondingly, techniques used in the neighboring fields are great foundations to build upon. THz radiation has been identified as a significant area of research with rich potential because of its location on the EM spectrum and its proximity to such well-developed fields. We would like to have the same control over THz radiation that we have over microwave radiation and visible light. In the past 20 years, much research has been dedicated to the advancement of THz techniques and devices, with the goal of filling this gap. The development of new THz generation and detection techniques [1] has greatly improved the capability of THz systems. In addition, the demonstration of passive photonic structures, like waveguides [1], gives us the means to better control THz radiation. Research has also been performed that envisions methods to provide better active manipulation of THz radiation. The development of effective THz modulators—particularly those that use an electrical approach—is an active research field, since it allows complex manipulation of THz beams, leading to a wide range of applications.

1.2. Terahertz Modulators

Early demonstrations of electrically controlled THz modulators were based on semiconducting two-dimensional electron-gas (2DEG) structures [2, 3] or birefringent liquid crystals [4]. However, each of these existing designs suffers from various drawbacks that limit their use, e.g., the requirement of cryogenic
temperature for operation [2], a limited modulation depth [3], or a slow modulation speed [4]. More recently, higher efficiency methods have been investigated, which, for example, take advantage of the controllable intraband transitions of graphene. Sensale-Rodriguez et al. highlighted the interesting applications graphene may have in the THz range by demonstrating a graphene-based electrical THz modulator with very low intrinsic signal attenuation, having the drawback of limited modulation depth [5]. The resolution of such weaknesses continues, as we have recently reported a technique for increased modulation depth in graphene-based modulators, via the use of ring-shaped apertures near the graphene layer [6]. Furthermore, extended, emergent opportunities have come from the development of metamaterials in which distinct materials can be integrated, forming hybrid metamaterial-based THz modulators with improved performance. Such modulators have been actively pursued with the expectation of overcoming the drawbacks facing current THz modulators [7-11].

1.3. Metamaterials

The development of artificially structured electro-magnetic materials, termed metamaterials, has led to the realization of phenomena that cannot be obtained with natural materials [12, 13]. These manufactured materials have specifically designed interactions with EM radiation, which gives them their optical properties. Typically, metamaterials gain their properties from the interaction of light with sub-wavelength structures that are engineered into the material. The geometry of the sub-structures that make up the array determine how the sub-
structures influence the bulk material properties; thus, by combining different structures, multiple properties can be tuned. This kind of material tuning has been demonstrated in the microwave region, with one such material having a negative index of refraction (requiring negative permittivity and permeability) [14]. Since this demonstration, metamaterials have been heavily investigated, with many proposed applications of technological importance across the EM spectrum [13, 15]. Furthermore, metamaterials, in general, have an interaction frequency that can be tuned by scaling the sub-structures that are engineered into the material. It is this property that makes metamaterials especially attractive for use at THz frequencies. Because they can be scaled into the THz region, metamaterials have the capability to extend THz technology beyond what natural materials alone can provide.

1.4. Structure of Thesis

In this thesis, I will introduce, in Chapter 1, the principles underlying planar metamaterials and will then discuss metamaterial modulators and sub-elements in Chapter 2. Chapter 3 will focus on the diffractive modulator design, which leads to a discussion of the experiment. Chapter 4 concludes the thesis and discusses the potential of metamaterials for future applications. The appendix contains information on mounting the device.
Of particular interest for THz modulation are planar metamaterials that can be electrically switched [16]. Electrical switching provides a mechanism for high-speed modulation of THz radiation, a promising result that is otherwise difficult to achieve. The ability to perform this switching stems from the design of the substrate and sub-elements that the metamaterial is comprised of. One such metamaterial device is shown in Figure 2.1a [7]. The metamaterial sub-elements have a geometry (termed OE2 [17]) shown in Figure 2.1b. Each element consists of two split-ring resonators (SRR) attached at the split-gap. Each ring provides an inductance, $L$, and the gap provides a capacitance, $C$, as shown in Figure 2.1c [7]. The two SRRs are oppositely wound, cancelling any magnetic response; thus, the remaining response is electric in origin, giving rise to the term electric split ring resonator (eSRR). This
sub-element structure results in a frequency dependent resonant response that is
dependent on the capacitance originating in the split-gaps. The metamaterial dies
were fabricated by our collaborators at the center for integrated nanotechnologies
(CINT). The substrate consists of a 1-µm-thick n-type GaAs epilayer \( n = 2 \times 10^{16} \text{ cm}^{-3} \) grown on a semi-insulating GaAs wafer by molecular beam epitaxy. The Ohmic
contact is fabricated using electron-beam deposition of 20 nm of nickel, 20 nm of
 germanium, and 150 nm of gold in sequence, followed by rapid thermal annealing at
350 °C for 1 min in a nitrogen atmosphere. Next, the planar array of elements is
fabricated using conventional photolithography and electron-beam deposition of a
10-nm-thick adhesion layer of titanium on the GaAs substrate, followed by 200 nm
of gold. The metal and n-GaAs form a Schottky junction and the connected
metamaterial resonators serve as a metallic gate [7]. This design allows for electrical control (via the application of a voltage to the sub-elements) of the conductivity in the split-gaps, which correspondingly tunes the resonant response [7]. The epilayer is chosen so that the extra free charge carriers short out the split-gap, meaning that when no external bias is applied to the Schottky contact, the resonant response is not present. However, when a reverse bias is applied to the Schottky contact, a depletion region is created in the doped epilayer underneath the sub-elements. This results in the free carriers being displaced from the gap which restores the capacitive response of the gap, resulting in the resonant response.

### 2.1. Terahertz Metamaterial Modulators

The device in Figure 2.1 shows a moderately high speed operation of a few kHz [7], but it performs with a modulation depth of only 3 dB. In fact, these types of planar metafilms generally exhibit a relatively low on/off ratio (< 10 dB [9]). Various related designs have been proposed to address this issue, including switchable plasmonic devices based on extraordinary optical transmission [18, 19], MEMS-based metamaterial devices [20], or devices based on metal-insulator transition materials, such as VO$_2$ that exhibit strongly temperature-dependent properties [21, 22]. As an alternative, one can take advantage of the fact that an array of metamaterial sub-elements can be grouped into ‘pixels’ [23], and that these groups can be engineered into patterns composing the overall structure of the array. We used this idea, and Chan et al. developed a THz spatial light modulator (SLM)
which had a pixelization scheme that used independently switchable groups of
eSRRs [23]. The pixels in the SLM were each formed into a square geometry
measuring 4 × 4 mm², and consisted of an array of 50 × 50 sub-elements. The entire
device was made up of 16 pixels laid out in a 4 × 4 grid, and the modulation depth of
the device was between 35% and 50% at the design frequency [23]. The ability to
group the sub-elements into individually controllable pixels permits us to design an
electrically controlled diffractive modulator in the spirit of a conventional acousto-
optic modulator [24]. Here we document the demonstration of a first-generation
device showing an electrically controllable diffraction pattern.

2.2. OE3 Type Sub-Element

The previous devices used metamaterials having sub-elements of the OE2
type (Figure 2.1b). This sub-element layout had several inefficiencies, and a new
sub-element (termed OE3 [17]) was designed by our collaborators at CINT as shown
in Figure 2.2a. The OE3 sub-element consists of four joined split rings, with their
gaps on the four outer corners, the major difference is that, in the OE3 sub-element,
the SRR split gaps are not isolated from the Ohmic contact as in the OE2 sub-
element. Other metamaterial design features remained the same. The important
concern here is how much of the external reverse bias is applied to the portions of
the sub-element near the split-gap. With the OE2 design, the voltage applied to the
gap is dependent on the depletion of the n-type layer under the outer ring. When the
reverse bias is increased, this depletion is greater, so the region inside the
outer-ring, including the split-gap, becomes progressively more isolated, dropping the voltage at the split-gap. In contrast, the split-gaps in the OE3 sub-element are on the outside of the element and are not subject to the isolation caused by the depletion of the outer ring, thus suffering from no limitation in performance [9]. The resonant response is again due to the inductive-capacitive coupling of the circulating currents. Figure 2.2b shows a numerical simulation of the surface current density on the sub-element from these currents when excited by normally incident THz radiation at the design frequency with the polarization shown[9]. We observe that the four loops again cancel out the magnetic response, resulting in a net electric response.

Figure 2.2. OE3 Metamaterial Sub-element
(a) Geometry of the updated sub-element. (b) Numerical simulation of surface current density excited from the inductive-capacitive resonance at the design frequency. (Source: [9])
Chapter 3

**Diffractive Modulator**

For the diffractive modulator device, the metamaterial consists of a planar array of sub-wavelength sized OE3 eSRRs fabricated on a 1-µm-thick n-doped GaAs epilayer grown on an intrinsic GaAs substrate [7-9]. The eSRR elements, as shown in Figure 3.1a, are interconnected with metallic wires and grouped into independent, periodic, columns each with a contact pad for external electrical control, shown in Figure 3.1b. As in previous switchable metamaterial devices [7-9, 23], the n-doped substrate epilayer effectively increases the damping (i.e., shorting out the split gaps) in the eSRRs, thus eliminating the $LC$ resonance of the metamaterial [7]. However, the application of a DC bias to the metallic structure creates a depletion region in the narrow gaps, which restores the capacitive split gaps and thus also the THz resonance [7].
Figure 3.1. Diffractive Modulator Detail
(a) Unit cell of the metamaterial, illustrating a single eSRR element in the reverse biased state. The dark gray region shows the higher carrier density in the n-doped GaAs epilayer, and the white region around the cutaway portion of the metal structure indicates the depletion upon a reverse voltage bias. (b) Schematic showing a portion of the first four “pixels,” which are composed of the eSRRs in (a) The eSRRs are patterned in rows, seven across, and interconnected, forming a Schottky gate; the pads of the first two even columns are displayed. (c) Illustration of the entire metamaterial grating (consisting of 32 columns). The color profile illustrates that alternate columns are biased forming a diffraction grating, with each column being independently controlled by the voltage bias between its Schottky pad and the Ohmic contacts.
The eSRR elements are grouped into ‘pixels’ that can be independently biased, using a similar concept to our previously reported SLM. The ‘pixels’ are rectangular in shape and form columns. Each column has a width of 596 µm and consists of rows of seven eSRRs. The eSRRs have an outer dimension of 68 µm, a metal strip width of 6 µm and thickness of 200 nm, a split gap of 2 µm, and a periodicity of 88 µm. In all, the device has 32 columns, as shown in Figure 3.1c, with two columns forming the periodic unit. The two columns are separated by 60 µm, allowing for connecting wires to their individual contact pads (the odd columns’ pads are along the bottom of the device and the even columns’ pads are along the top). With this design each column can be addressed by an external voltage, and the metamaterial resonance can be switched on and off. The spacing between consecutive two-column units is 20 µm, the same as the spacing between eSRRs. This gives a two-column periodicity of \( d = 1272 \mu m \). The final metamaterial device has an active area of \( 19.6 \times 20.3 \text{ mm}^2 \).

The size and structure of the eSRR elements are chosen so that a metamaterial resonance occurs at 0.4 THz (corresponding to a free-space wavelength \( \lambda_0 = 0.75 \text{ mm} \)). This wavelength \( \lambda_0 \) is comparable to the column width of the device. When we apply a DC bias to alternate columns, the transmission at the resonance frequency will be modulated periodically across the face of the device. In this configuration, the device operates as a grating, and so we would expect to observe radiation diffracted at an angle to the normally incident direction. The first-order diffraction angle is given by \( \sin(\theta) = \lambda / d \), which corresponds to \( \theta = 36.1^\circ \) at \( \lambda_0 \).
If we remove the DC bias from all of the columns (or apply it equally to all columns), then the diffracted beam should disappear since there is no longer a periodic variation of the transmission function. Thus, as we apply and remove a voltage from alternate columns of the metamaterial, we expect that the diffracted signal will be modulated with a very large dynamic range because in the diffraction direction the signal should be effectively background-free.

### 3.1. Experimental Setup

To observe the expected diffraction, we characterize our device using a THz time-domain spectroscopy system in transmission geometry with fiber-coupled photoconductive antennae for both THz generation and detection (see Figure 3.2). The linearly polarized THz beam is collimated and directed towards the
The THz electric field amplitude modulation of the metamaterial at normal incidence, showing the effect of applied gate bias on the metamaterial resonance at 400 GHz.

metamaterial at normal incidence with the polarization of the THz electric field oriented parallel to the long axis of the metamaterial columns, i.e., in the vertical direction and perpendicular to the interconnecting metal wires [6]. The THz beam spot on the device has a diameter (1/e) of approximately 6 mm, which is large enough to illuminate numerous columns but small enough to avoid scattering from the metal mounting hardware at the edges of the device. The back surface of the GaAs substrate is uncoated, making further device optimization using an anti-reflection coating possible. The receiver is positioned at a distance of 25 cm from the device at various angular positions relative to the axis of the incident beam.
3.2. Methods & Results

We measure the THz signal using two methods. In the first method, we apply a DC voltage bias to alternate (or all) metamaterial columns and insert an optical chopper into the THz beam before it interacts with the device, using a lock-in amplifier referenced to the chopper frequency. With this method, we are able to directly measure the diffracted beam as well as the zero-order beam. Therefore, this configuration permits us to determine the strength of the on-axis metamaterial modulation, the diffraction efficiency, and the insertion loss. Figure 3.3 shows the spectra of the transmitted zero-order radiation under normal incidence using this measurement method. When a reverse voltage bias (−13 volts) is applied to all columns of the metamaterial array, we clearly observe the spectral dip at the designed metamaterial resonance frequency of 400 GHz (shown in red). This is in contrast to the absence of a spectral feature when the columns are all grounded (shown in black).

In the second method, we apply a square-wave AC voltage oscillating between 0 and -13 volts at 1 kHz to alternate (or all) metamaterial columns. This frequency is also used as the reference to a lock-in amplifier. Thus, we are essentially performing a differential measurement that provides the signal difference between the diffracted signals with and without electrical bias. In experiments with normal incidence, we sweep the receiver angle and keep the distance to the device fixed. Figure 3.4a shows the measured signal (using the
Figure 3.4. Angle Sweep Measurement
(a) The angular dependence of the differential diffracted THz electric field amplitude at 400 GHz, when applying an alternating bias at 1 kHz to the device. A strong diffracted signal at ~36° is observed when alternate columns are biased (red), creating a diffraction grating. In contrast, when all columns are biased (black) the grating effect disappears. (b) The intensity spectra of the differential signals diffracted at 36.1°, when applying an alternating bias at 1 kHz to the device. A 22 dB modulation depth is achieved at 400 GHz. The red curve shows the intensity when alternate columns are biased (acting as a grating). In contrast, the black curve represents the background, showing the intensity when all of the columns are biased.
second method) as a function of receiver angular position. Here, we obtain THz waveforms at each receiver angular position and then extract the magnitude of the spectral component at 0.4 THz by Fourier transform. We display the results for two different biasing conditions. The red curve shows the differential signal when the AC bias is applied to alternate columns, representing the relative strength of the diffracted signal. In contrast, the black curve shows the differential signal when the same AC bias is applied to all of the columns, so that no diffraction should occur, representing the background signal. Nominally, the background should be zero in the diffraction direction; however, some small background signal is observed, due to two possible factors. First, small random scattering may occur due to roughness or imperfections in the eSRR pattern. Second, the normally incident Gaussian beam may be slightly diffracted naturally after passing through the device, resulting in a small signal even at large angles to the normal direction. The effect of diffraction is likely more dominant; however, we are unable to experimentally rule out the effect of scattering from roughness. Nevertheless, when the bias is applied to alternate columns, we observe a clear signature of diffraction at 0.4 THz at an angle of $\theta = \sim 36^\circ$, consistent with the anticipated diffraction angle for this grating geometry. To determine the modulation capability of our device, we investigate the entire available spectrum (not just the 400 GHz component) at the angle of the diffraction peak. Figure 3.4b shows the spectral response at the peak of the first-order diffracted signal (i.e., at $\theta = 36.1^\circ$), plotted on a log scale. We observe a modulation depth of $\sim 22$ dB at the design frequency of 400 GHz. This represents the largest
Figure 3.5. Angle Sweep Map
The spectra of the differential signals diffracted at various receiver angles, when applying an alternating bias at 1 kHz to the device, with the AC bias applied to alternate columns. The grayscale represents the THz electric field amplitude on a logarithmic scale. The prominent features at small angles from the axis indicate the normally transmitted beam. The arc—dropping from large angles at low frequency to smaller angles at high frequency—represents the angle and frequency dependent broadband first-order diffraction from the device. Also illustrated is the weaker second-order diffraction. The colored curves show the theoretically expected diffraction angle vs. frequency curves for first-order (green) and second-order (red) diffraction.
The dynamic range of an electrically controlled THz modulator yet reported.

It has been shown that these electrically switchable eSRR arrays exhibit correlated amplitude and phase modulation over a relatively broad bandwidth, not merely at the frequency of the eSRR resonance [9]. Thus we anticipate that other frequency components of the broadband THz illumination will also be diffracted at angles determined by the grating equation. Consequently, we can expect to measure a diffracted signal in a wide range of angles, with different spectral components diffracting in different directions. This is confirmed by the data in Figure 3.5, which shows the spectrally resolved measurements as a function of angle. This data set was acquired by applying the AC bias to alternate columns, which measures the differential signal (using the second method), as in Figure 3.4a. This figure clearly shows the expected signature of THz radiation diffracted over a broad spectral bandwidth, with the diffracted signal continuously shifting to larger angles with increasing wavelength. A weaker second-order diffraction signature is also observed at larger angles. The theoretically predicted relation between the frequency and the angle of diffraction is shown in the figure for the first two diffraction orders (green and red lines, respectively). This result confirms the broadband nature of the modulation imposed upon the THz field by the metamaterial.

Furthermore, using the first method, with a DC bias on the device, we can estimate the overall diffraction efficiency of the grating. At the design frequency of 0.4 THz and at the optimal diffraction angle of 36.1°, the power diffraction efficiency
is approximately 0.53\%. This value has room for improvement: possible modifications include stacking multiple metamaterial layers or further optimizing the resonance by adjusting the eSRR and epilayer parameters. The insertion loss of the device is 9.4 dB, due in part to the back-surface reflection, as noted above. Further improvement is possible by implementing other strategies of device architecture, for instance, using freestanding thin-film metamaterials that exhibit anomalous refraction [25].
Chapter 4

Conclusions

We have demonstrated a diffractive modulator for THz radiation based on a switchable planar metamaterial. At the metamaterial resonance frequency, this modulator provides a dynamic range in excess of 20 dB, the largest yet reported for an electrically driven THz modulator. The device also exhibits broadband performance, due to the combination of amplitude and phase modulation properties of the metamaterial. We also note that the interaction length of incident EM radiation with the metamaterial is quite low (having a thickness of only 200 nm). Our results indicate that the dynamic range and the diffraction efficiency are not strongly frequency-dependent over a range of at least several hundred GHz, due to the correlated amplitude and phase response of the eSRR array. In addition, the freedom to tailor the metamaterial resonances and pixelization offers a powerful
strategy for further optimization of the device performance. Beyond free-space modulators, metamaterials show many potential uses for the manipulation of THz radiation. As an example, it has been shown that THz surface waves will propagate on the surface of planar metamaterials [26]. Surface waves propagating on a metamaterial would have much larger interaction lengths with the metamaterial, which could lead to superior modulation performance. Careful tailoring of the metamaterial elements, pixelization, and voltage control could also force surface wave decoupling of desired frequencies at various points along the device. We surmise that metamaterials have an important part to play in the emerging THz technology field.
Appendix

Mounting Details

Mounting the metamaterial dies proved to be non-trivial. The metamaterial dies shipped as pre-cut GaAs wafers. In order to perform our experiments with the devices it was necessary to develop a mounting solution that met several criteria. The mount would need to physically support the die in the required orientation, without blocking the desired beam axis for THz propagation. The mounting solution would also need to facilitate our ability to tune the voltage bias of the columns of eSRRs, and ideally it would allow us to swap between the various metamaterial devices we have without difficulty.

Our final solution consisted of a 3M Test & Burn-In PGA Kit Socket with a 20 mm × 20 mm square hole cut by the Rice machine shop (as seen in Figure 4.1a). This kit comes in varieties of both 0.05” and 0.1” hole pitch. The pad spacing on the metamaterial dies is 0.05” pitch, but the 0.05” kit does not support do-it-yourself pin layout. Instead, 3M will insert the pins to specifications, this is because the closing mechanism is more complicated in the 0.05” pitch kit, making it more difficult to cut the required size hole. For these reasons, we chose the 0.1” pitch PGA kit. The PGA was assembled and the pins were inserted as shown in Figure 4.1a. We ordered perfboard of 0.1” pitch to match the PGA kit, and we also ordered rows of pins from Samtec with 0.1” pitch in order to build the PGA-to-die interface (Figure 4.1b). This
interface was made by inserting the pins into the perfboard at the required positions to match the assembled PGA kit, while leaving space for the die in the center. The pins were adhered to the perfboard using a cyanoacrylate adhesive (super-glue). Then, in the final step, the metamaterial die was attached to the perfboard using a tosylamide-formaldehyde resin (nail polish) applied to the corners of the die, with the active region centered above the opening in the perfboard.

An important criterion of the mounting solution was the electrical connection, in order to tune the voltages of the device columns we needed to wire-bond the pads on the die to the pins on the perfboard. Wire-bonding is a method of

Figure 4.1. Mounting Design (Left) Schematic of the PGA with center hole (faded white) machined out. The gold circles are sites with pins; the dark gray circles are inactive sites. (Right) Schematic of the perfboard (holes not shown).
creating electrical connections between metallic surfaces; the wire-bonder uses fine gold wire (12.5 um) which is placed in contact with a surface at the desired bond location. The wedge holding the wire then emits ultrasonic pulses, causing local melting of the wire and surface, resulting in a strong weld. We chose gold plated pins to facilitate the wire-bonding but, unfortunately, the tips of the pins had a slight taper, ending in a point and were not flat as we had expected. Because the tips were pyramidal, the wire-bonder was not able to apply the force necessary to create a bond, instead the downwards directed force displaced the sample to the side. Even after securing the sample to the wire bonding stage a good bond could not be made because the bonding area was too small. To solve this problem, we modified the pins, by filing the pins to a flat tip in order to increase the bonding area. We found, however, that the core of the pin was much harder than the soft gold plating and was thus unable to make good bonds. We then decided to sputter gold on the filed pins to create a better bonding surface. We tried various thicknesses of gold, starting with a 60nm gold layer and moving to 90nm. With some persistence, we were able to bond with reasonable reliability from one pin to another pin on the perfboard interface. Though we were able to successfully wire-bond for each device, the process was still difficult. More than 10 bonding attempts were necessary before a solid bond was made, and even then, the bonds were fragile; bonds were made starting with the pin bond in order to minimize possible damage to the metamaterial device. The overall wire-bonding procedure was to repeatedly attempt to bond with the pins, which had a successful bond rate of 5-10%. Once a
successful bond was made with the pins, the second bond to the metamaterial die (completing the connection) was attempted. Bonding to the clean gold surface of the metamaterial pads was significantly easier with a successful bond rate of >90%.

The most important reason that wire-bonding success rates were low is that the wire-bonder must use significant force when pressing the wire into the surface during the application of the ultrasonic pulses in order to make a good bond. During typical wire-bonding, the surface will be very flat, so that there is no lateral motion caused by the applied downwards force. In our case, the pins were mostly flat, but the shaving was not perfect. This was coupled with a slight tilt which originated from how the pins were glued into the perfboard; both of these resulted in the effect that when the bonder pressed down, the device would not remain stationary and, instead, jerked to the side, resulting with the bonding tip in contact with the perfboard, not the pin. To solve this problem, we inserted the perfboard interface into a breadboard and then used vices to hold the breadboard to the bonding stage. This kept the device in the correct general area; however, the breadboard had a slight bend to it, and there was still some room for the device to wiggle, meaning when the wire-bonder pressed down, it would move slightly in reference to the wire/contact area, resulting in a weaker bond. In order to compensate for the possibility that we would not be able to bond to some of the pins we used copper perfboard for the final two perfboard samples. The copper perfboard was able to be bonded to and if we bonded from a pad to the copper surrounding a pin we could then solder from the pin to the bond. We never ended up needing to do this,
although it may still be a good idea to reduce the fragility of the bonds. Once the devices were finished they could fit into the PGA which was mounted on an optic grip on a translation stage. The pins on the back of the PGA were connected to our circuit by way of 0.1” pitch ribbon cables that were purchased from Samtec. The cables did not make very good contact with the pins on the back of the PGA but after physically bending the pins it was possible to get a reliable connection. Once the device was put into the PGA with the cables connected we tested continuity in order to ensure that each pin was isolated from the rest and that each pin had good contact to the circuit.

Two important things that should be done in the future are to order pins that do not have the taper; this would significantly increase the bonding success rate because it would allow for a large, smooth, and pure bonding surface, it would also be good to order ribbon cables that will make better connection to the PGA pins.


