Impedance-matching Analysis in IR Leaky-wave Antennas

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ABSTRACT

Planar leaky-wave antennas (LWA) that are capable of full-space scanning have long since been the pursuit for applications including, but not limited to, integration onto vehicles and into cameras for wide-angle of view beam-steering. Such a leaky-wave surface (LWS) was designed for long-wave infrared frequencies with frequency scanning capability. The LWS is based on a microstrip patch array design of a leaky-wave impedance surface and is made up of gold microstrip patches on a grounded zinc sulphide substrate. A 1D composite right/left-handed (CRLH) metamaterial made by periodically stacking a unit cell of the LWS in the longitudinal direction to form a LWA was designed. This paper deals with loading the LWA with a nickel bolometer to collect leaky-wave signals. The LWA radiates a backward leaking wave at 30 degrees at 28.3THz and scans through broadside for frequencies 20THz through 40THz. The paper deals with effectively placing the bolometer in order for the collected signal to exhibit the designed frequency regime. An effective way to maximize the power coupling into the load from the antenna is also explored. The benefit of such a metamaterial/holographic antenna-coupled detector is its ability to provide appreciable capture cross-sections while delivering smart signals to sub-wavelength sized detectors. Due to their high-gain, low-profile, fast response time of the detector and ease of fabrication, this IR LWA-coupled bolometer harbors great potential in the areas of high resolution, uncooled, infrared imaging.

Keywords: Leaky-wave antennas, CRLH metamaterials, bolometer, long-wave infrared, frequency scanning.

1. INTRODUCTION

A planar leaky-wave surface (LWS) design at long-wave infrared (LWIR) wavelengths was proposed[1]. Much work has been done to characterize the loading of planar antennas at IR wavelengths. A popular theory revolves around coupling a line to the antenna and loading the line with a photon or thermal detector[2-4]. This paper analyzes the loading of a transmission line coupled leaky-wave antenna. The key takeaway from the loading method is to preserve the leaky-wave signal characteristics as seen in[1].

2. LEAKY-WAVE ANTENNA

An antenna based on a microstrip patch array design of a leaky-wave impedance surface is made up of an array of periodically placed gold (Au) patches on Au microstrip, lying on a grounded zinc sulphide (ZnS) substrate. The purpose of the LWS was to produce beam scanning within the LWIR range (7.5-15µm) with a leaking angle of θ=-30 degrees with respect to the normal to the LWA (backward leaking) at 10.6µm. A single unit cell contains a patch of x ×y dimensions 2.674µm ×2.157µm respectively. The substrate has a thickness of 0.65µm while the patch and ground plane are, respectively, 75nm and 100nm thick. A unit cell containing an Au patch has x ×y dimensions 3.75µm ×4.3625µm. When stacked periodically in both x and y directions, it forms a 2D antenna array that follows the beam scanning behavior mentioned above. This paper deals with loading a 1D LWA based on this unit cell.

Plasmonics: Metallic Nanostructures and Their Optical Properties XIII, edited by Allan D. Boardman, Din Ping Tsai,
Proc. of SPIE Vol. 9547, 954722 · © 2015 SPIE · CCC code: 0277-786X/15/$18 · doi: 10.1117/12.2188601

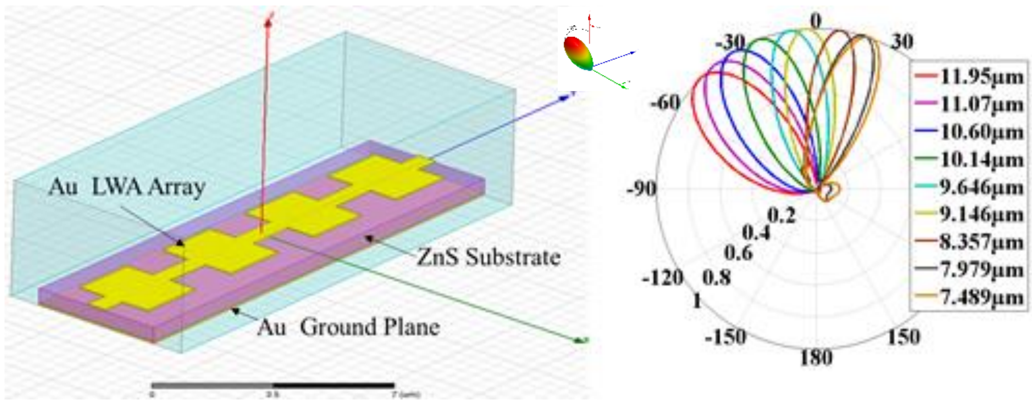

Figure 1: IR leaky-wave antenna array (a) geometry (b) frequency scanning behavior with θ=-30º beam at 10.6μm in the YZ (φ=90º) plane.

The LWA was designed and simulated using ANSYS HFSS software in driven modal solution type. Fig. 1(a) shows an array of periodically placed patches on a microstrip line. The structure was illuminated by incident plane waves at LWIR wavelengths 7.5-15μm, each wave incident on the LWA at angles -60 to 60 degrees. In transmitting mode, the leaky TM_0 mode produces angular scanning in the far-field, the angles with the respect to the normal to the structure given by:

$$\theta = \sin^{-1}\left[\frac{\beta(\omega)}{k_o}\right] = \sin^{-1}\left[\frac{c\beta(\omega)}{\omega}\right] \tag{1}$$

where β(ω) is modal phase propagation constant, k_o is angular wave number in free space, and ω is angular frequency. Since β is a function of frequency, beam steering is achieved by frequency scanning[8-10].

3. BOLOMETER COUPLED LWA

A method for IR detection using a nickel (Ni) bolometer load was proposed. The challenge is determining a suitable location to place the load in order to couple the leaky-wave signal from the LWA into the detector. The frequency scanning regime described by the transmitting LWA is shown in Fig. 1(b). A Ni load of $x \times y$ dimensions 0.65μm × 0.1μm is loaded on an Au transmission line of $x \times y$ dimensions 0.65μm × 20μm coupled to either side of the LWA array for symmetry. The backward leaky-wave signal couples into the LWA and propagates down the structure into the localized Ni load as shown in Fig. 2.

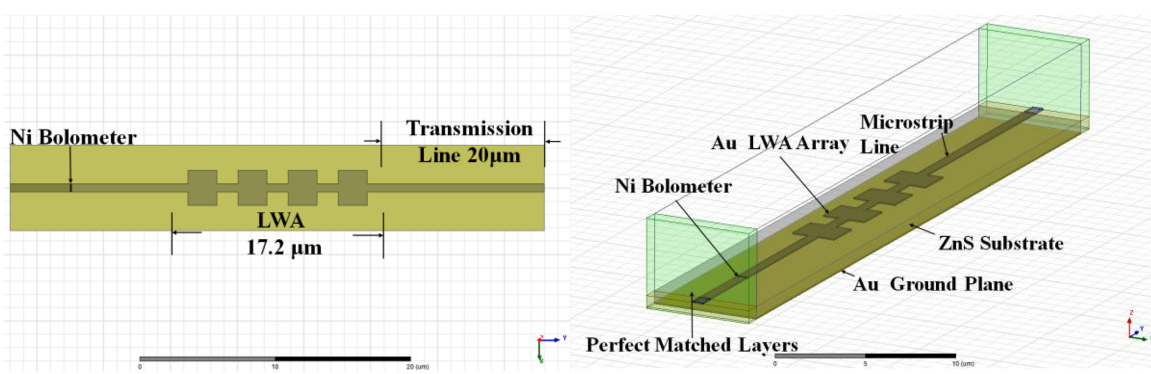

Figure 2: Geometry of IR LWA loaded with Ni bolometer.

Perfectly matched layers and radiation boundaries are added to the simulation setup to terminate waves at the model boundary. The volume loss density P_v in the Ni load is computed in HFSS as:

$$P_v = \frac{1}{2}\mathrm{Re}\left(\tilde{E}\cdot\tilde{J} + j\omega\tilde{B}\cdot\tilde{H}\right) = \frac{1}{2}\mathrm{Re}\left(\tilde{E}\cdot\tilde{J} + \nabla\times\tilde{E}\cdot\tilde{H}\right) \quad (2)$$

When integrated over the volume of the load, it gives the power dissipated in the bolometer. A peak in the power dissipated in the load at a certain frequency and at angle θ, determines the direction at which the incident wave achieved maximum coupling and thus characterizes the leakage/detection angle at that frequency.

The power dissipated in the Ni bolometer is plotted against incident angles for an incident wave of wavelength 10.6µm. The distance *D* of the bolometer from the LWA is along the line. Fig. 3 shows the variation of the angles at which the normalized peak power dissipated is observed for different locations along the transmission line.

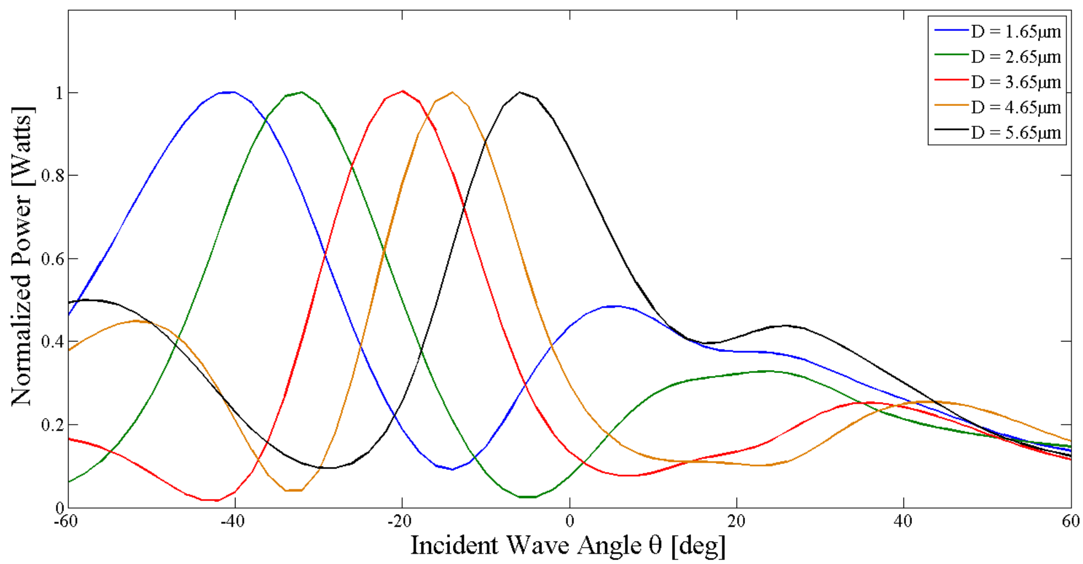

Figure 3: Normalized power dissipated in Ni bolometer versus incident wave angle for different distances *D* of bolometer, from the LWA, on the transmission line.

The varying angles of peak power occur due to a combination of line losses, phase propagation and reflections due to impedance mismatch at the antenna-bolometer interface. A simple solution to achieve reciprocity in the receiving mode case is to tune the position of the load along the line in order to achieve the desired angle of peak power dissipation in the load. As seen in fig. 3, peak dissipated power was observed at -30 degrees for an incident wave of wavelength 10.6µm for the bolometer distance D = 2.65µm from leaky-wave antenna, which corresponds to a quarter-wavelength distance at 10.6µm. Fig. 4 shows the power dissipated in the Ni bolometer versus a sweep of incident wave angles for waves of different wavelengths. The frequency scanning regime described by the power dissipated in the load is consistent with what is seen in the reciprocally transmitting LWA case (Fig. 1(b)) and is an indication of concurrence between the receiving and transmitting models.

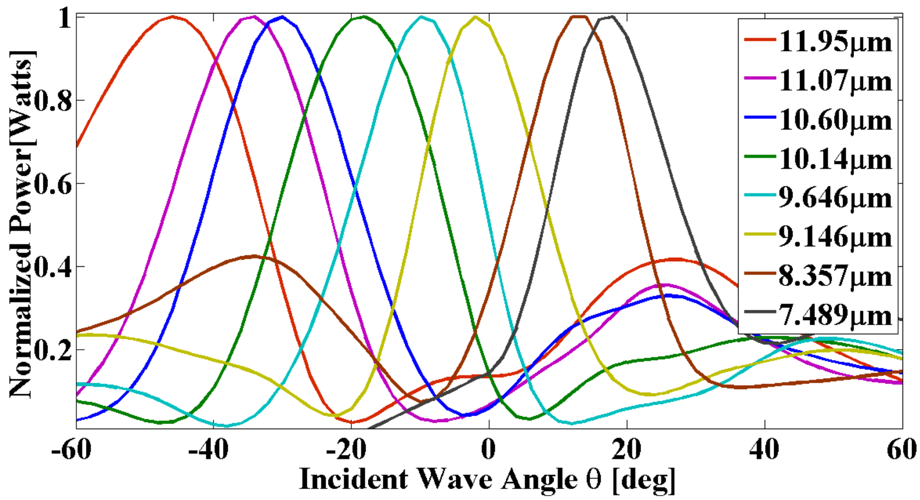

Figure 4: Frequency scanning behavior of the signal collected in the bolometer with -30° at 10.6µm and near broad side at 9.15µm for a bolometer placed 2.65µm away from the LWA.

Nickel bolometer is a resistive element constructed from a material with a very small thermal capacity and large temperature coefficient of resistance (TCR). so that the absorbed radiation produces a large change in resistance. The LWA-coupled nickel bolometer would be operated by passing a bias current through the bolometer and the change in output voltage, due to a large change in resistance, caused by absorbing the leaky-wave signal, would be monitored. By reducing the size of the nickel absorber, a lower amount of energy will be needed to increase its temperature which will result in more sensitive detection. A smaller bolometer will also have a smaller time constant which can be useful for high frame-rate applications[7,10]. Increasing the size however would increase the total power absorbed in the load, and this is especially desirable when impedance matching and coupling efficiency are prerogatives. The Ni load length is increased to 100µm to absorb over a larger surface area. Fig. 5 shows an improvement of about two orders of magnitude.

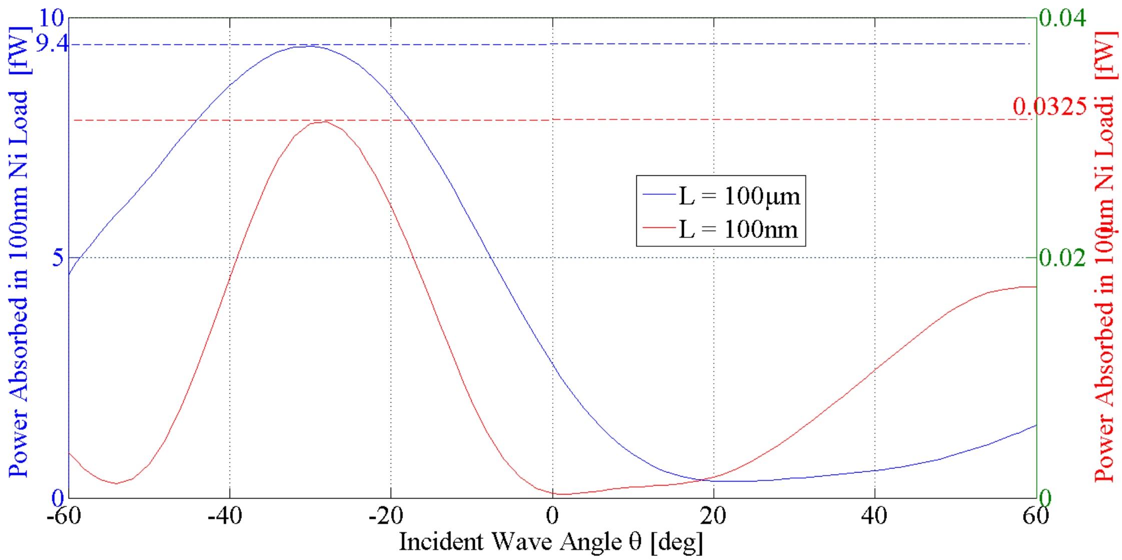

Figure 5: Improvement in power absorbed in Ni load through extension of load length.

Increasing the length of the transmission line bolometer doesn't affect the power absorbed in the bolometer beyond 100μm of load length. Additionally, varying the width of the transmission line type load only decreases the amount of power coupling into the load. Fig. 6 shows power absorbed in the load for varying widths of the transmission line load. The width corresponding to that of the gold transmission line leading away from LWA seems to be the width of the load required for maximum power transfer. In order to further increase the power in the Ni load, alternatives need to be sought out for. Thus the load is matched to the line. When considering the fundamental nature of the antenna, which is basically a line on which periodic perturbations in the form of patches are present, matching a load to the guiding mode, i.e. transmission line load would be suitable.

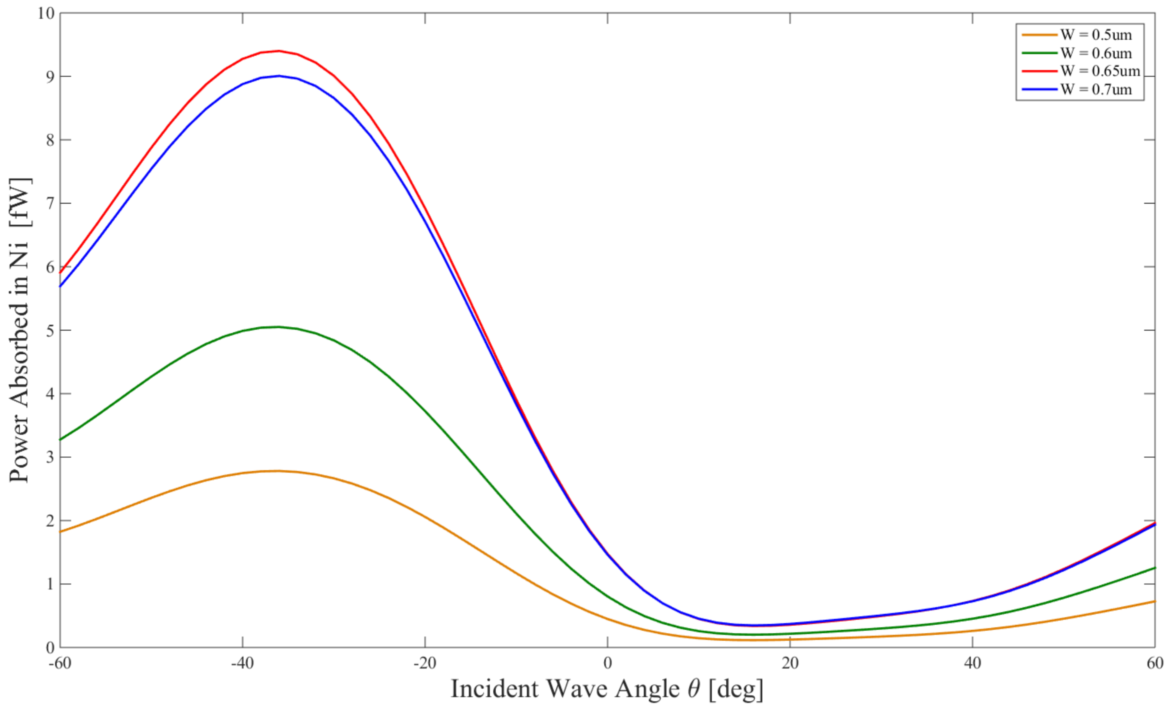

Figure 6: Variation in power absorbed in Ni load for different widths of transmission line type load.

4. CONCLUSION

An IR planar leaky-wave antenna made up of an array of grounded Au patches on a ZnS substrate was loaded with a Ni bolometer. The bolometer was loaded on a transmission line coupled to the antenna and the structure was illuminated with incident waves at varying angles of incidence with respect to the normal to the structure. The angle at which peak power dissipated in the Ni bolometer was found to vary with position of the bolometer on the load due to a combination of line losses, phase propagation and reflections due to the impedance matching of the load and antenna.

The position of the load on the transmission line pertaining to a peak power dissipation occurring at -30^o incidence was for a 10.6μm wave found to be 2.65μm (quarter-wave distance) away from the antenna. Frequency scanning at this point further confirmed that the signal collected at the load is the leaky-wave signal. Increasing the length of the transmission line type load to 100μm, further serves to increase the power coupling into the load. This paper characterizes preliminary steps towards loading an IR leaky-wave antenna-matching a load to the guided mode of a series-fed leaky-wave antenna. Thermal response of the infrared antenna would provide additional information on the absorption of infrared energy and validate the findings. Further research on this topic will reveal optimized methods of loading such metasurfaces and will hopefully pave the wave towards the goal of lensless imaging.

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