Antenna-Coupled Infrared Detectors for Imaging Applications

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***Abstract*—Infrared focal plane arrays (IRFPAs) are a critical component in advanced infrared imaging systems. IRFPAs are made up of two parts, a detector array and a readout integrated circuit (ROIC) multiplexer. Current ROIC technology has typical pitch sizes of 20×20 to 50×50 μm^2. In order to make antenna-coupled detectors suited for infrared imaging systems, two-dimensional (2-D) arrays have been fabricated that cover a whole pixel area with the penalty of increasing the noise figure of the detector and, therefore, reducing its performance. By coupling a Fresnel zone plate lens to a single element antenna-coupled detector, infrared radiation can be collected over a typical pixel area and still keep low-noise levels. A Fresnel zone plate lens coupled to a single-element square-spiral-coupled infrared detector has been fabricated and its performance compared to single element antenna-coupled detectors and 2-D arrays of antenna coupled detectors. Measurements made at 10.6 μm showed a two-order-of-magnitude increase in *SNR* and a $\sim 3\times$ increase in D^* as compared to 2-D arrays of antenna-coupled detectors.**

***Index Terms*—Antenna-coupled detectors, Fresnel zone plate lenses, infrared focal plane array (IRFPA), microbolometer.**

I. Introduction

THE DEMAND for inexpensive infrared systems has grown for both civilian and military applications for use as night vision, target acquisition, aerial navigation, commercial aircraft landing, and smoke penetration systems. Infrared focal plane arrays (IRFPAs) are a critical component needed for advanced infrared imaging systems. IRFPAs are made up of two components: a detector array and a readout integrated circuit (ROIC) multiplexer [1]. Thermal imaging systems in widespread use today employ photon detectors for the detector array, with the great disadvantage that this type of detectors have to be cooled down to temperatures well below 300 K. In contrast to photon detectors, thermal detectors do not require cooling to exhibit adequate sensitivity. The tradeoff, however, is that their photoresponse is relatively slow compared to that of most photon detectors [2].

Bolometers are resistive elements constructed from materials with a high temperature coefficient of resistance (TCR) so that absorbed radiation will produce a change in resistance. They are operated by passing a bias current through them and monitoring the output voltage; a change in the output voltage will reflect changes in resistance [3], [4].

Reducing the size of the bolometer sensor will increase its sensitivity: it will take smaller amounts of energy to induce a high temperature rise and will also make the detector faster; a smaller mass will increase its temperature in less time than a larger mass detector. The problem with small bolometers is that the amount of energy that falls into the detector will also be small; however, the collection area of a small bolometer can be increased by coupling an antenna to it, this would result in a fast and more sensitive detector that can operate at room temperature [5], [6].

Current ROIC technology have typical pitch sizes of 20×20 to 50×50 μm^2; two-dimensional (2-D) arrays have been fabricated that cover a whole pixel area [7], [8]. The problem with this type of detector is that adding elements in series to cover a bigger area will increase the total noise of the detector and will reduce its performance.

The main noise source in a microbolometer is Johnson noise, which is given by

$$V_j = \sqrt{4KTR\Delta f} \quad (1)$$

where K is the Boltzmann constant, T is the temperature in Kelvin, R is the resistance of the microbolometer, and Δf is the bandwidth of the measurement. By making an $N \times N$ array of microbolometers, the total resistance of the detector will increase by a factor of N^2. From (1), we can see that this will result in a $N\times$ increase in Johnson noise.

In order to keep the noise low, at the level of a single-element microbolometer, but still have a large collection area, a Fresnel zone plate lens (FZPL) was fabricated to collect infrared energy and focus it on a single antenna-coupled microbolometer; the performance of these devices is compared to that of a 2-D array of detectors and to a single-element detector.

II. Fabrication

A square-spiral antenna was used to couple infrared radiation into a nickel bolometer (Fig. 1). Square-spiral antennas are considered "frequency independent antennas," since their geometrical configuration can be described just by angles [9]. The lower limit of their bandwidth depends on the outer circumference of the spiral, and the upper limit depends on the configuration near the feed point. Spiral antennas present circular

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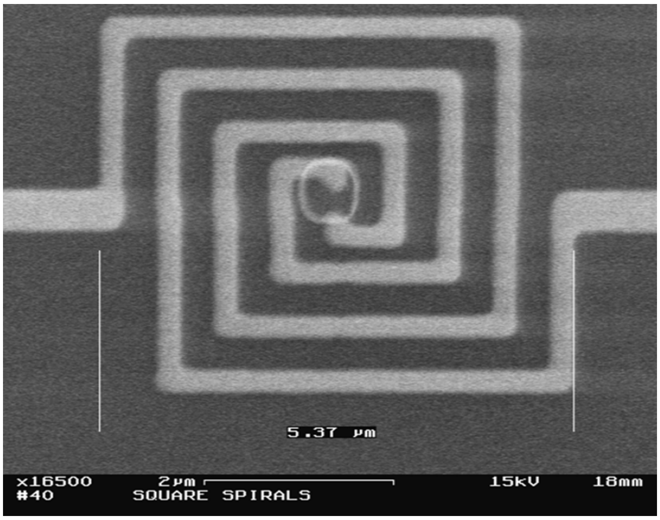

Fig. 1. Single-element square-spiral antenna coupled to a nickel microbolometer.

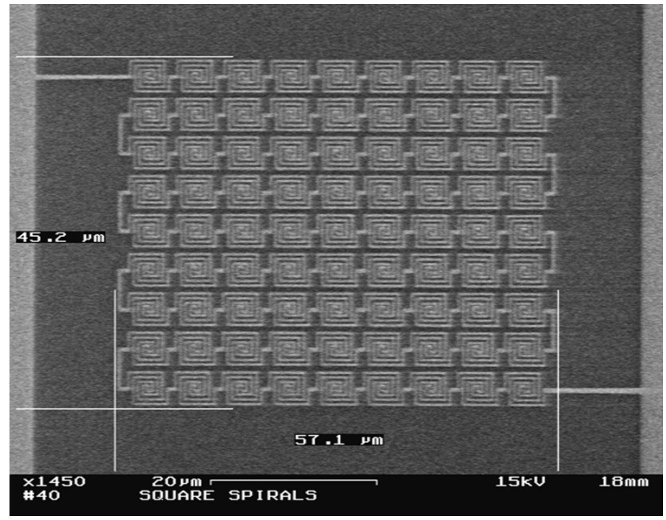

Fig. 2. Two-dimensional array of antenna-coupled microbolometers.

polarization with a sense that depends on the winding sense of the spirals. A square-spiral antenna is regarded as a counterpart of a round-spiral antenna with the advantage that it offers a size reduction of 22% (based on the increase of perimeter from πD to $4D$) [10].

The entire antenna-coupled detector was patterned using electron-beam lithography and liftoff. All the devices tested were patterned on 4-in, 380-μm-thick Si substrates with 200 nm of thermally grown SiO_2 for thermal and electrical isolation. The antennas were made of 100 nm of e-beam evaporated Au over a 5-nm layer of Cr used as an adhesion layer. The bolometric sensor at the feed of the antennas is a sputtered 0.5 μm$\times$ 0.3 μm patch of Ni. The width of the antenna arms is around 200 nm and a single arm of the spiral is around 17 μm long. All the antennas fabricated have 200-nm-wide gold lines that go from the antenna to the the bondpads for DC biasing purposes. A set of 2-D arrays of antenna coupled microbolometers that cover an area close to 50×50 μm^2 were also fabricated using the same materials and method used for the single-element antenna-coupled detectors (Fig. 2).

The FZPLs were patterned using optical lithography and aligned to single-element square-spiral-coupled microbolometers on the backside of the wafer using an EV620 backside aligner. The FZPLs were made of 100 nm of e-beam evaporated Au over a 5-nm layer of Cr. The FZPL was designed to work at a wavelength of 10.6 μm with a focal length of 380 μm so that the antenna-coupled detector would be at its focus; the FZPL had a diameter of 200 μm and consisted of five clear Fresnel zones (Fig. 3). The main function of the zone plate is to increase the gain of the spiral antenna; the zone plate will also reduce the energy loss due to guided waves in the substrate by altering the boundary conditions of the dielectric slab waveguide [11].

III. Characterization

The processed wafers were diced into 1-cm^2 chips and wire bonded into specially made chip carriers. Testing of the devices was done using a CO_2 laser at 10.6 μm focused by an $F/8$ optical train which had an almost diffraction-limited spot with a $1/e^2$ radius of 200 μm and an irradiance of 17.6 W/cm^2 at the focus. The measurements were made with the radiation coming from the substrate, which means that the FZP was used in its transmissive mode.

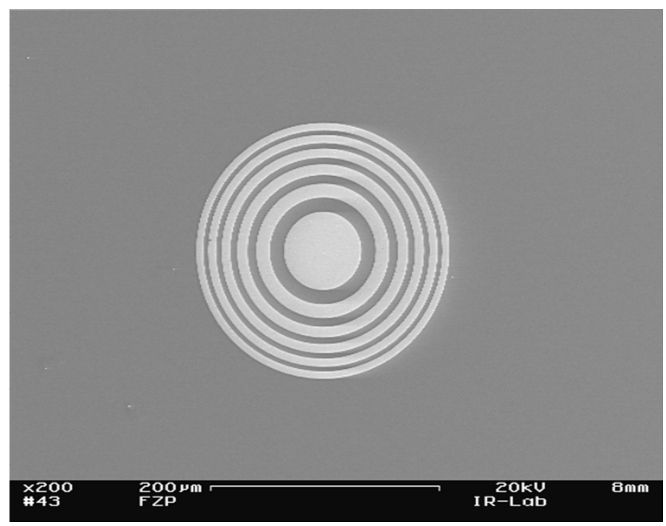

Fig. 3. Fresnel zone plate lens used to focus infrared energy on a single element antenna-coupled microbolometer.

Noise measurements were made using an HP3562A Dynamic Signal Analyzer which has a measurement range of 64 μHz to 100 kHz. The noise introduced by the signal analyzer was attenuated by a factor of $1000\times$ referred to the noise of the detector by amplifying the signal of the detector $1000\times$ before measuring it with the signal analyzer.

Response measurements were taken using the test setup shown in Fig. 4. For signal-to-noise (SNR) calculations, noise and response measurements were taken at the same level of amplification. The total response of the devices in volts was recorded directly from the lockin amplifier.

Angular response measurements were taken by rotating the stage with respect to the the optical axis in 1° increments and recording the response of the device. After every rotation, the X, Y, and Z positions had to be readjusted to center the device at the focus of the laser beam. This was done by adjusting the

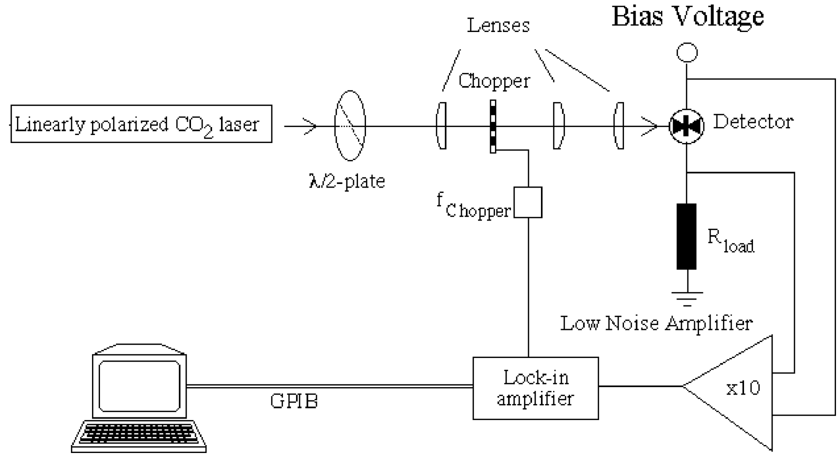

Fig. 4. Test setup used to characterize antenna-coupled infrared detectors.

TABLE I
MEASUREMENTS AND FIGURES OF MERIT FOR A SINGLE-ELEMENT 2-D ARRAY AND FZP-COUPLED ANTENNA-COUPLED DETECTORS

	SNR	A_d	D^*
Single	$\sim 2,860$	25 μm^2	$3.2\times 10^4 \frac{cm\ \sqrt{Hz}}{W}$
2D-Array	$\sim 24,\ 500$	2,576 μm^2	$2.7\times 10^4 \frac{cm\ \sqrt{Hz}}{W}$
FZP	$\sim 330,\ 000$	31,415 μm^2	$9.5\times 10^4 \frac{cm\ \sqrt{Hz}}{W}$

position of the device until the maximum response of the device was obtained. The use of high $F/\#$ optics ($F/8$) to focus the CO_2 laser on the detector reduces the effect of the convolution of the antenna pattern with the angular distribution of the focused light cone [6].

The single-element square-spiral antennas presented a dc resistance of around 200 Ω, while the 2-D arrays of square spirals had a resistance of around 1.5 kΩ. All the detectors measured were biased at the same bias current of 0.5 mA, and their response measured using a 10 $\times$ amplifier.

IV. RESULTS

Noise and response measurements at 10.6 μm were made; the single-element square-spiral antennas gave a response of 10 $\pm$ 1 μV and a noise figure of 3.5 $\pm$ 0.3 nV/$\sqrt{\text{Hz}}$. The 2-D array of square-spiral antennas presented a response of 135 $\pm$ 3 μV with a noise figure of 5.5 ± 0.8 nV/$\sqrt{\text{Hz}}$, while the FZP-coupled detectors presented a response of 1.1 $\pm$ 0.1 mV and the noise figure was 3.5 $\pm$ 0.2 nV/$\sqrt{\text{Hz}}$, the same as the one for single-element detectors without an FZPL.

D^* is a figure of merit that permits comparison of detectors of the same type but having different areas. It is widely used for infrared detectors, and it is defined as the SNR in a 1-Hz bandwidth per unit incident radiant power per square root of detector area [2]

$$D^* = \frac{\sqrt{A_d \cdot \Delta f}}{\Phi_e}\text{SNR} \tag{2}$$

where A_d is the area of the detector, Φ_e is the radiant power that falls on the detector, and Δf is the frequency bandwidth used to make the noise measurements.

Table I shows the D^* values obtained for the three detectors measured. From this table we can see how the SNR of a single element compared to a 2-D array had an increase of around 8.6 $\times$, which is close to the 9 $\times$ theoretical increase for a 9 $\times$ 9 array; however, D^*, which is the main figure of merit for infrared detectors, did not change. This is also expected, since D^* is a figure of merit normalized to the area of the detector; therefore, increasing the area of the same type of detector will not change its D^*.

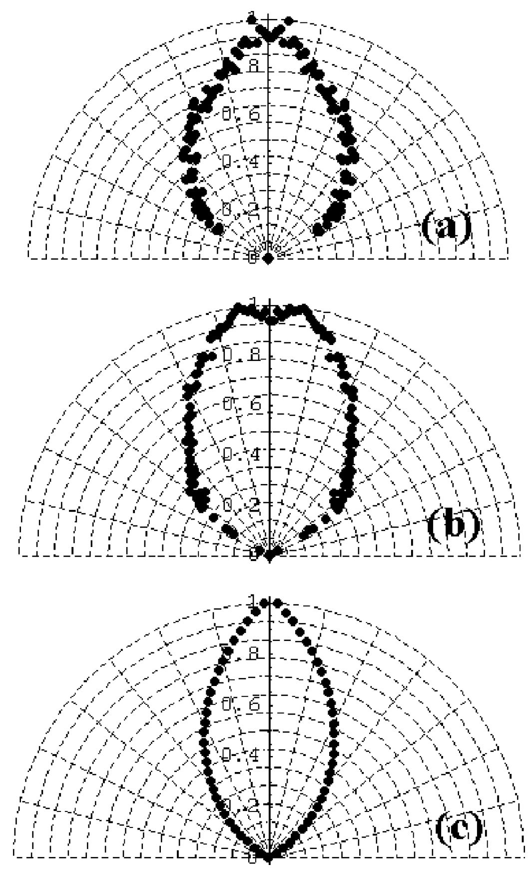

Fig. 5. Radiation patterns of spiral antennas. (a) Single element. (b) Two-dimensional array. (c) FZP-coupled antenna.

Angular response measurements were made on the three types of detectors (Fig. 5). The FZP-coupled antenna presented a more directive radiation pattern than the other two antenna-coupled detector configurations, a result that agrees with the radiation patterns shown in [11] for millimeter-wave antennas coupled to transmissive FZPLs. The computed directivity for the 2-D array is 1.6 with a 50×50 μm^2 area, and the FZP has a directivity of 4.1 for an area of 31 415 μm^2 (100-μm-radius zone). With the FZP-coupled detector, we gain $2.5\times$ in directivity with an area increase of $12.5\times$.

V. Conclusion

A new type of infrared detector that consists of an FZP coupled to an antenna-coupled detector has been fabricated and measured. This detector can be integrated into an ROIC and be used in infrared imaging applications.

The performance of the FZPL coupled to a single-element square-spiral-coupled infrared detector has been compared to single-element antenna-coupled detectors and 2-D arrays of antenna coupled detectors. Measurements made at 10.6 μm showed a two order of magnitude increase in SNR, and a $\sim 3\times$ increase in D^* of the FZP-coupled detectors compared to 2-D arrays of antenna-coupled detectors. Radiation patterns were also performed on all the detectors fabricated; the FZP-coupled detectors presented a sharper main lobe than the other types of detectors, which agrees with measurements made on similar devices at millimeter wavelengths.

The D^* numbers obtained for FZP-coupled detectors are still shy of the values reported for infrared detectors used in commercial applications. This value can be further increased by using a higher TCR material for the bolometer (e.g., VOx) and by thermally isolating the detector from the substrate.

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Javier Alda, photograph and biography not available at the time of publication.

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