Modulation-transfer function measurement of SPRITE detectors: sine-wave response

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A method is presented for measuring the modulation transfer function of signal processing in the element (SPRITE) detectors with a HgCdTe composition optimized for the 3–5-μm band. This method incorporates a 3.39-μm He–Ne laser to generate Young's fringes of varying spatial frequency, which are scanned across the detector elements. The results are consistent with theoretical models for these devices and indicate a limited resolution capability for SPRITE detectors used for the 3–5-μm band.

I. Introduction

The signal processing in the element (SPRITE) detector is a device used in serial-scan thermal-imaging systems to perform an internal time-delay-and-integration operation on photogenerated carriers to improve signal-to-noise ratio (SNR) without complex external electronics.[1,2] The three-terminal n-type HgCdTe device is shown in Fig. 1. An applied electric field across the structure from a constant current source causes photogenerated carriers to drift along the bar with an ambipolar velocity v_a. The infrared image is mechanically scanned at a velocity v_s that matches the ambipolar drift velocity. As the image is scanned, the signal adds coherently and the noise adds incoherently to produce an enhancement of the SNR at the readout terminal. This time-delay-and-integration operation is performed without external circuitry to implement delay line and summation operations, thus reducing system complexity.

Resolution of SPRITE detectors is limited by both carrier diffusion and readout geometry.[3] We present a method of measuring the modulation transfer function (MTF's) of SPRITE detectors fabricated for operation over the 3–5-μm band. A 3.39-μm He–Ne laser is used to generate Young's fringes of varying spatial frequency that are mechanically scanned across the SPRITE's. The MTF is determined from the modulation depth of the output signal. Various-length SPRITE detectors with tapered and bifurcated readout geometries are studied. The measured MTF's are compared with the theoretical predictions[4,5] of MTF based on detector geometry and operating parameters.

II. Equipment

The setup used for the MTF measurements is shown in Fig. 2. The laser source was a 3.39-μm He–Ne laser with a linearly polarized TEM_{00} output power of 25 mW. Output power was adjusted with a wire grid polarizer. After expansion to a 25-mm diameter, the beam was focused on a dual-pinhole aperture to produce Young's fringes. Different apertures provided various spatial frequency fringes. A 10-sided rotating polygon mirror performed the scanning operation of the fringes across the SPRITE bars. The output of the detector was amplified by a low-noise preamplifier, and the modulation depth of the signal was measured on an oscilloscope.

The pinhole apertures were designed based on flux throughput, the required spatial frequency of the fringes at the detector plane, and the acceptable diffraction envelope resulting from the diameter of the holes. Based on a 20-cm aperture-to-detector distance, the spacing of the pinholes was chosen to be 1.0–4.0 mm in steps of 0.5 mm. These choices produced spatial frequencies up to ~6 cycles/mm. The diameter of the pinholes was chosen to provide the largest diffraction envelope at the detector plane while still allowing a reasonable flux throughput. Based on these considerations, a pinhole diameter of 100 μm was used for these measurements.

The SPRITE detectors were packaged in an enclosure with a sapphire window. This package was housed in a liquid-nitrogen Dewar with a $CaCl_2$ win-

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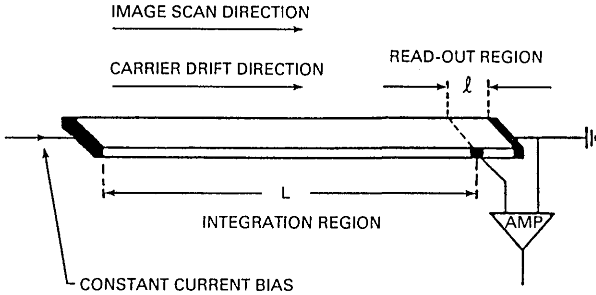

Fig. 1. SPRITE detector geometry.

dow. For all the MTF measurements the detectors were held at a temperature of 190 K.

III. System Calibration

A calibration procedure was required before each particular spatial frequency measurement to maintain a constant modulation depth of the fringes incident upon the detectors required. For each spatial frequency measurement, the polygon scanner was removed and a Ge lens was used to image the illuminated pinhole aperture onto a pyroelectric vidicon. The laser output was chopped at 8 Hz for proper vidicon imaging. The video output of the vidicon was examined on a line-by-line basis in the vicinity of the pinhole signal, and the pinhole aperture was positioned to produce maximum and equal signal levels for both pinholes. Maintaining an equal flux output from both pinholes guaranteed a constant input modulation for all measurements. After the calibration was completed, the polygon scanner was replaced and positioned to give the best output signal from the SPRITE's.

IV. Modulation transfer function measurements

SPRITE detector bias conditions for the MTF measurements were based on a fixed scan velocity of 67 m/s for the optical signal across the detectors. The value of the bias field across the detector needed to produce the required scan velocity is found from the ambipolar drift velocity of the carriers in the material and is given by the relation

$$v_a = \mu_a E, \tag{1}$$

where μ_a is the ambipolar mobility and E is the electric field across the bar. Using a previously published value for mobility in 3–5-μm optimized HgCdTe (Ref. 2) of $\mu_a \approx 150\ \text{cm}^2/(\text{V}\cdot\text{s})$ gives $E = 44.7$ V/cm. This value of the bias electric field was used for all measurements. Initially, the polygon scanner velocity was set to give the correct scan velocity based on the distance between the scanner and the detector plane. The scanner velocity was then fine tuned until the maximum output modulation from the SPRITE's was obtained. A typical detector output for an input spatial frequency of 4.3 cycles/mm is shown in Fig. 3. The modulation depth was measured at the point where the diffraction envelope peaked on the oscilloscope trace.

The SPRITE detector packages used for these measurements consisted of a set of 700-μm bars with bifurcated readouts, a set of 400-μm bars with tapered readouts, and a set of multiple-length bars with lengths of 450–650 μm and tapered readouts. Photographs of the 700-μm detectors and various-length detectors are shown in Figs. 4 and 5, respectively. The three detector sets were produced from different boules of HgCdTe material so some variation in device characteristics could be expected.

Based on previous analyses of SPRITE detectors, the MTF depends on diffusion processes and detector

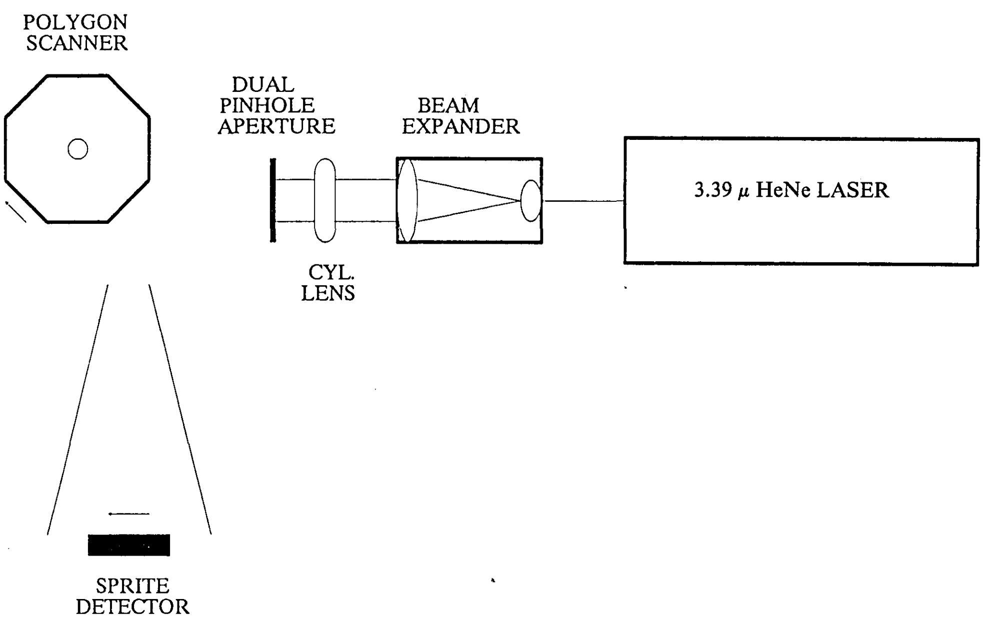

Fig. 2. Measurement setup.

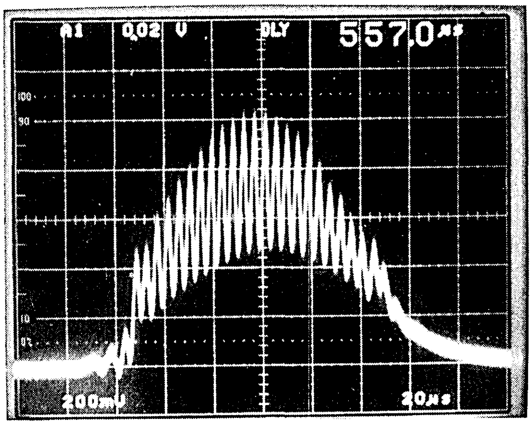

Fig. 3. Typical detector output signal with scanned fringe input.

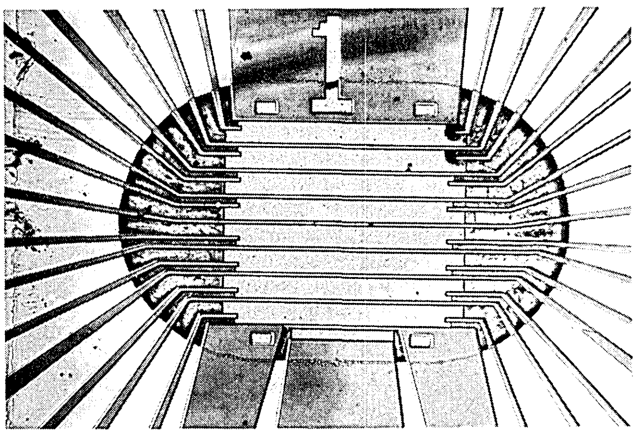

Fig. 4. Photograph of 700-μm SPRITE detectors with bifurcated readouts.

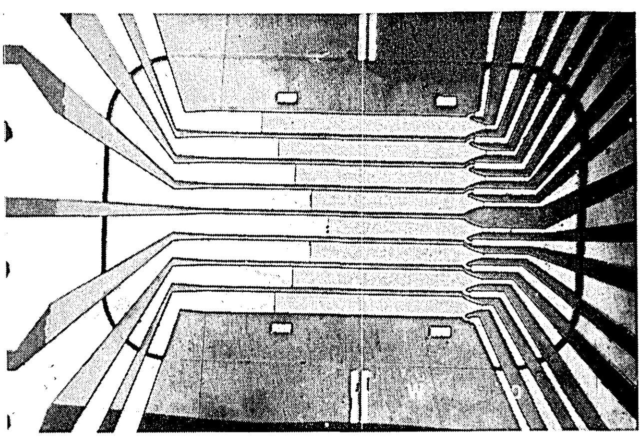

Fig. 5. Photograph of various-length SPRITE detectors (450–650 μm) with tapered readouts.

readout geometry. For the along-scan direction, the diffusion MTF can be written as[4]

$$\mathrm{MTF}_d(\xi, L) = \frac{1 - \exp\left\{-[L_D^2(2\pi\xi)^2 + 1]\,\dfrac{L}{\mu E\tau}\right\}}{[L_D^2(2\pi\xi)^2 + 1]\left\{1 - \exp\left[-\left(\dfrac{L}{\mu E\tau}\right)\right]\right\}}, \tag{2}$$

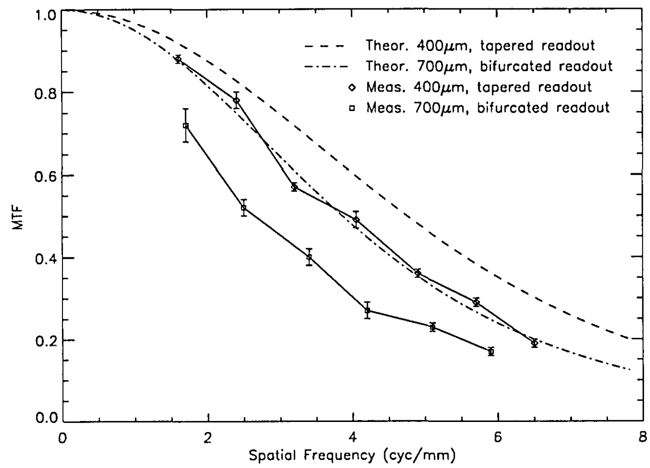

Fig. 6. Measured and theoretical MTF of 400-μm (tapered readout) and 700-μm (bifurcated readout) SPRITE detectors.

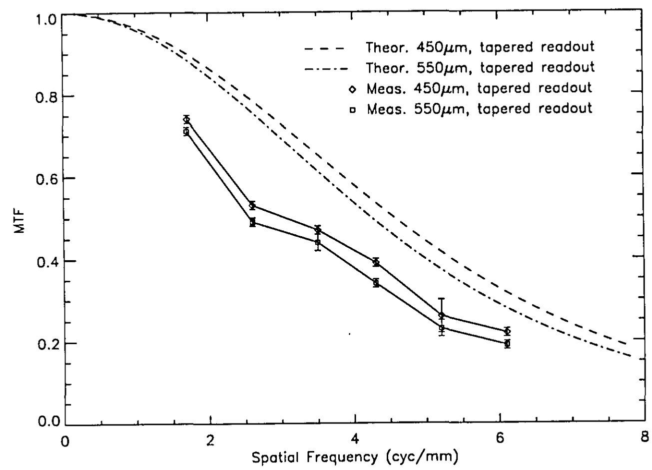

Fig. 7. Measured and theoretical MTF of 450-μm and 550-μm SPRITE detectors with tapered readouts.

where ξ is the along-scan spatial frequency, L is the SPRITE bar length, L_D is the diffusion length, μ is the ambipolar mobility, τ is the carrier lifetime, and E is the bias field. The MTF from the readout alone is given by the Fourier transform of the y profile of the readout as[5]

$$\mathrm{MTF}_r(\xi) = \mathcal{F}\left[\mathrm{rect}\left(\frac{x - X/2}{X}\right)\exp(-\alpha x)\right]. \tag{3}$$

The variables are the following: x is the along-scan direction, X is the along-scan length of the readout, ξ is the along-scan spatial frequency, and α represents the taper coefficient of the readout. The total MTF can be expressed as a product of the diffusion and readout geometry MTFs as[6]

$$\mathrm{MTF} = \mathrm{MTF}_d \times \mathrm{MTF}_r. \tag{4}$$

Measured and theoretical MTF curves for the 700-μm (bifurcated readout) and 400-μm (tapered readout) SPRITE bars are shown in Fig. 6. Figure 7 shows the measured and theoretical MTF of the 450- and

Table I. Values Used in Calculation of Theoretical MTF

Carrier lifetime	τ	15 μs
Hole mobility	μ_h	150 $cm^2/V \cdot s$
Hole diffusion constant	D_h	2.5 cm^2/s
Hole diffusion length	L_D	61.2 μm
Electric field	E	44.7 V/cm
Readout length	X	62.5 μm
Taper coefficient		
(Tapered readout)	α	0.0228 μm^{-1}
(Bifurcated readout)	α	0 μm^{-1}

550-μm SPRITE bars (both with tapered readouts). The theoretical MTF curves were calculated from Eq. (4) by using the values of the variables from Refs. 2 and 5 given in Table I. The MTF's of the SPRITE's were normalized to unity at zero spatial frequency by dividing the measured output modulation depth by the input modulation depth of the fringes. The input modulation depth was measured with a 25 μm × 25 μm HgCdTe detector that was scanned across a stationary fringe of 1.0 cycle/mm. The measured modulation depth was then corrected by the value of the MTF of a 25 μm × 25 μm detector at 1.0 cycle/mm, giving an input modulation depth of 0.94.

A comparison of measured MTF's versus theoretical MTF's in Figs. 6 and 7 indicates that, although the analytical model is optimistic, there is good agreement regarding the dependence on bar length and readout geometry. Comparing MTF curves for two different pairs of structures (700 μm bifurcated and 400 μm tapered; 450 and 550 μm tapered), we find that the difference in MTF as a function of spatial frequency is consistent between theoretical and experimental curves.

V. Conclusions

The present theoretical model is obviously optimistic in the prediction of MTF performance. The only parameters that have so far been included in the model are those of carrier diffusion, bar length, and readout geometry. Other effects will need to be included in the model if we are to obtain more accurate predictions, such as carrier accumulation effects at the contacts[7] and the variation in ambipolar mobility resulting from the integration of background flux along the length of the SPRITE bar.[8]

Comparing the sine-wave response method with other methods for measuring MTF's of SPRITE's, such as the impulse response method[9,10] we find advantages and disadvantages of each method. The main disadvantage to the sine wave method is that different spatial frequencies require a separate measurement. Use of an impulse response measures the MTF at all frequencies at once. One advantage of the sine-wave method arises from the fact that the impulse response can drive the detector in a nonlinear fashion. The sine-wave target projected onto the SPRITE is a closer approximation to an actual scene irradiance distribution. In addition, the sine-wave method is capable of supplying a signal even at spatial frequencies that would be absent (or present only in small amounts) from a focused-spot input. This characteristic can be useful for increasing the SNR of MTF's at high frequencies.

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