Scanned-fringe, spatial-harmonic-distortion test for detector nonlinearity

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Abstract. Results are presented for a modification of the spatial-harmonic-distortion test, suitable for nonlinearity measurement of single-element detectors, using a scanned-fringe technique and an electronic spectrum analyzer. Detector nonlinearity of less than 1% was measured at a wavelength of 10.6 μm. Previously, the smallest measured nonlinearity for the spatial-harmonic-distortion test was of the order of 3%, using a stationary-fringe technique and an 8-bit frame grabber.

Subject terms: infrared technology; detectors, nonlinearity; spatial-harmonic-distortion test.

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1 Introduction

Detector nonlinearity can be measured using techniques[1] that include the flat-field method,[2,3] the superposition method,[4] and the beat-frequency method.[5] A convenient method for measurement of small nonlinearities in both individual detectors and focal plane arrays is the spatial-harmonic-distortion method. Diffraction is used to generate and project spatial sine waves of irradiance onto the detector. Nonlinearities in the detector responsivity cause harmonic distortions, which can be seen in the Fourier spectrum of the detector output voltage. When we used a stationary interference fringe to measure the average nonlinearity of focal plane arrays,[6] the smallest nonlinearity measured was of the order of 3%, limited by the spatial noise of the detector-to-detector responsivity variations and by the quantization noise of the 8-bit frame grabber. For the present case of nonlinearity measurements of individual detector elements, the minimum measurable nonlinearity levels are determined by residual nonlinearities in the apparatus that generates the interference fringe. Minimum measurable nonlinearity levels for single-element detectors are demonstrated to be less than 1% at a wavelength of 10.6 μm using this technique.

2 Theory

The basis of the spatial-harmonic-distortion test for detector nonlinearity is that sinusoidal waveforms, which are eigenfunctions of linear systems, are not eigenfunctions for a system with a nonlinear transfer characteristic. An input sinusoid is distorted by a nonlinear system such that the output consists of the original frequency, along with harmonic-distortion terms. The magnitudes of the harmonic-distortion terms indicate the strength of the nonlinearity present.

We create appropriate sinusoidal input functions using Young's double-slit interference. A double-slit aperture of spacing b is uniformly illuminated by a coherent source of wavelength λ, which produces in the far field a sinusoidal irradiance variation with a spatial frequency ξ proportional to the slit spacing and inversely proportional to the product of the wavelength and the propagation distance:

$$\xi = \frac{b}{\lambda z} \ . \tag{1}$$

Because the width a of the slits is nonzero, an envelope function $w(x)$ that multiplies the fringe pattern occurs:

$$w(x) = \left[\frac{\sin(\pi a x/\lambda z)}{(\pi a x/\lambda z)} \right]^2 \ . \tag{2}$$

This envelope function is of no concern in our experiments because we use only the central fringe of the diffraction pattern, for which $w(x) \approx 1$ for the particular values of a, b, z, x, and λ used.

3 Experimental Techniques

The instrumentation shown in Fig. 1 was used to generate, project, and scan the interference fringes across the detector under test. To demonstrate the technique, two different de-

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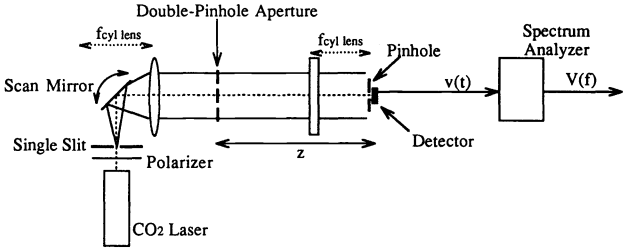


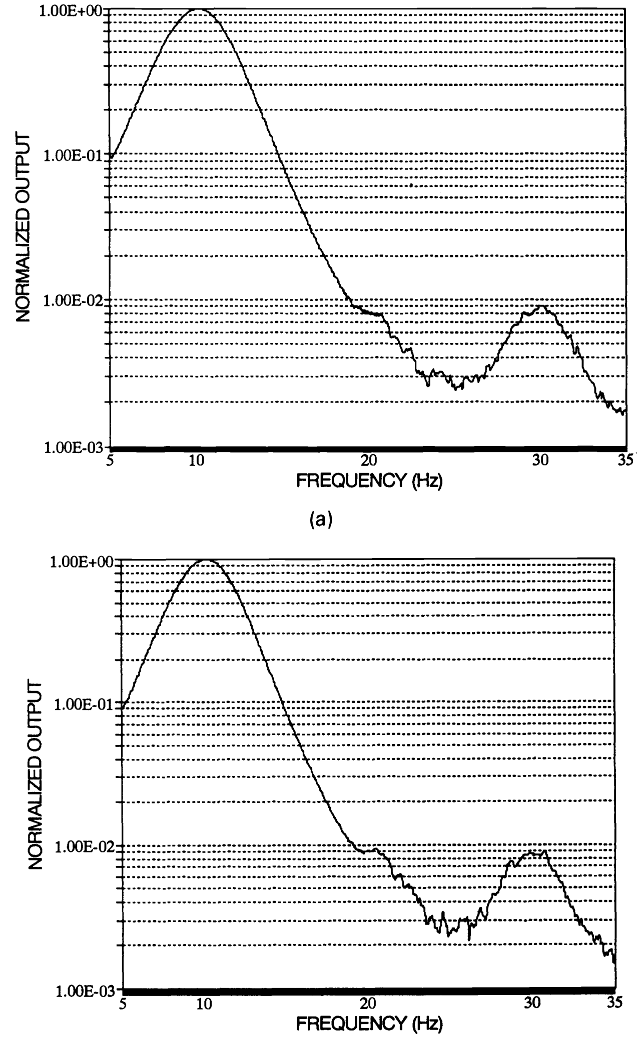
Fig. 1 Apparatus used to generate, project, and scan the interference fringes across the detector. The CO_2 laser operated at a wavelength of 10.6 μm. The scan mirror oscillated at a frequency of 10 Hz. The cylinder lenses each had a focal length of 300 mm. The single slit was adjustable, with an opening width of approximately 0.5 mm.The pinholes were 0.5 mm in diameter, spaced by 5 mm. The distance *z* from the double-pinhole aperture to the detector was 2 m, yielding a fringe period of 4.2 mm at the plane of the detector. Two different detectors were tested: a pyroelectric and a HgCdTe.

tectors were evaluated at two different irradiance levels: a pyroelectric (Eltec Model #406) and a HgCdTe photoconductor (Judson J15D) were both evaluated at irradiances of 6.3×10^{-5} W/cm^2 and 2.4×10^{-4} W/cm^2. The pyroelectric detector had a circular 2-mm-diam active area. A 200-μm-wide slit was placed 2 mm in front of the element, to avoid spatial-averaging effects, which would otherwise decrease the contrast of the detected fringes. The photoconductor had an active area of 0.16×0.16 mm, sufficiently small that no pinhole was necessary to obtain good contrast fringes.

The CO_2 laser (California Laser, model LS55) operated at a wavelength of 10.6 μm. The polarizer immediately following the laser provided control of the irradiance levels delivered to the detector under test. Detectors generally have a more linear response under small-signal conditions, such as when the incident power is of the order of the noise-equivalent power (NEP), than at higher flux levels, which tend to introduce saturation effects in both the detector and preamplifier.

The scan mirror oscillated at a frequency of 10 Hz (dictated by the frequency response of the pyroelectric detector) and moved the interference-fringe pattern back and forth across the detector. The amplitude of the motion was adjusted so that only the central maximum fringe of the interference pattern was scanned back and forth past the detector. The use of only the central fringe of the interference pattern avoids introduction of harmonic distortion from the envelope function of Eq. (2). However, in using only the central fringe, the adjustment of the scan mirror is critical to achieve minimum instrumental harmonic distortion. The scan mirror must reverse direction just as the minimum of the central fringe moves past the edge of the photosensitive area. Observation of an oscilloscope trace of the detector output aids in adjustment of the scan amplitude, so that the detector output appears to be a continuous sinusoid, without introducing discontinuities and their inherent distortion, which would otherwise result if the scan reversal occurred at a point other than that of minimum irradiance.

The cylinder lenses each had a focal length of 300 mm. The first cylinder lens was oriented to collimate in the narrow direction of the slit (adjustable, around 0.5 mm wide), and the lens position was adjusted to give equal irradiances at both pinholes. The double-pinhole aperture consisted of two 0.5-mm-diam pinholes, spaced by 5 mm. The second cylinder lens was oriented in the orthogonal direction, and served only to concentrate the irradiance onto the detector, without changing the fringe spacing. The distance *z* from the double-pinhole aperture to the detector was 2 m, yielding a fringe period of 4.2 mm at the plane of the detector, using Eq. (1).



(a)

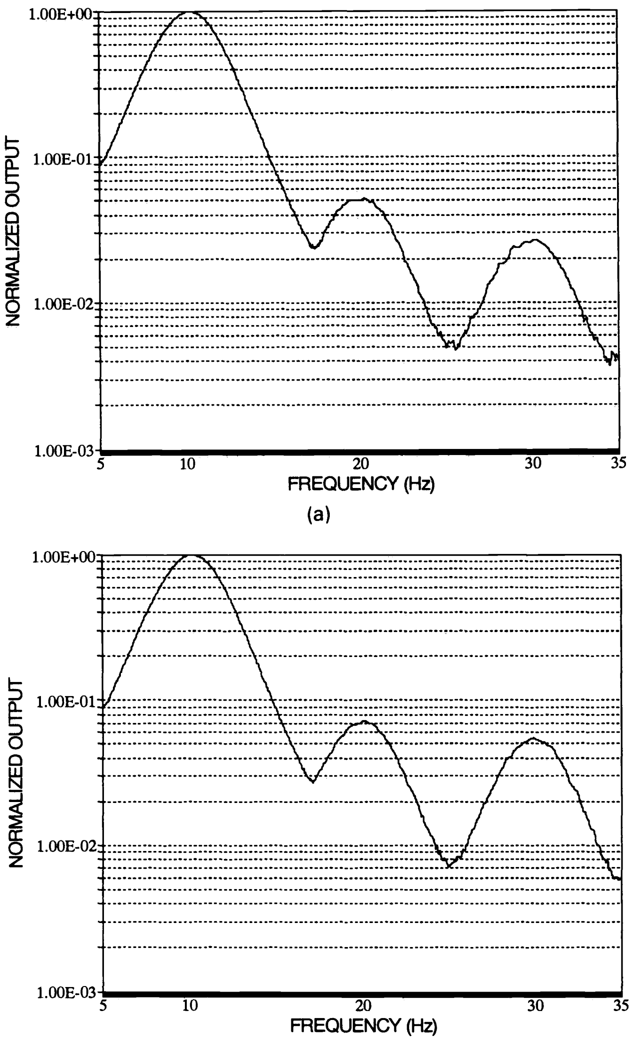
(b)

Fig. 2 Measured spectrum for the pyroelectric detector. (a) Detector-plane irradiance is 6.3×10^{-5} W/cm^2. Distortion is 0.8% for the second harmonic and 0.9% for the third harmonic. The rms noise level is approximately 0.1% of the fundamental. (b) Detector-plane irradiance is 2.4×10^{-4} W/cm^2. Distortion is 0.9% for the second harmonic and 0.8% for the third harmonic. The rms noise level is approximately 0.1% of the fundamental.

The spectrum analyzer was a Hewlett-Packard model #3585B. The harmonic-distortion specification of the spectrum analyzer was −80 dB, well below the residual harmonic distortion seen in the measurements. The frequency bandwidth of the measurements was the minimum for the instrument, 3 Hz.

4 Results

The pyroelectric detector exhibited a very linear response, with measured harmonic-distortion levels of 0.8% (second harmonic) and 0.9% (third harmonic) for an irradiance level of 6.3×10^{-5} W/cm^2 [Fig. 2(a)] and distortion levels of 0.9%



(a)

(b)

Fig. 3 Measured spectrum for the photoconductive detector. (a) Detector-plane irradiance is 6.3×10^{-5} W/cm^2. Distortion is 5% for the second harmonic and 2.6% for the third harmonic. The rms noise level is approximately 0.1% of the fundamental. (b) Detector-plane irradiance is 2.4×10^{-4} W/cm^2. Distortion is 7% for the second harmonic and 5.5% for the third harmonic. The rms noise level is approximately 0.1% of the fundamental.

(second harmonic) and 0.8% (third harmonic) for an irradiance level of 2.4×10^{-4} W/cm^2 [Fig. 2(b)]. The standard deviation for each point of the spectrum was calculated over a data set consisting of 10 spectra taken under identical conditions and was found to be approximately 0.1% of the fundamental. These harmonic distortion measurements show that the pyroelectric detector is linear to within 1% over the measured range of irradiances. The fact that the nonlinearity does not appreciably change within that range indicates the presence of instrumental nonlinearity rather than detector nonlinearity. The measured harmonic-distortion levels around 0.9% for the pyroelectric detector are around a factor of 3 lower than the minimum measurable nonlinearities of Ref. 6.

Not surprisingly, the HgCdTe photoconductor showed a higher level of nonlinearity. At the lower irradiance level of 6.3×10^{-5} W/cm^2, the second harmonic was 5% and the third harmonic was 2.6% [Fig. 3(a)]. When the irradiance increased to 2.4×10^{-4} W/cm^2, the second harmonic increased to 7%, and the third harmonic increased to 5.5% [Fig. 3(b)]. The standard deviations of these spectra were calculated in a fashion similar to that of the pyroelectric detector data, and again found to be approximately 0.1% of the fundamental. As expected, higher irradiance levels produce higher harmonic-distortion levels for a detector with a nonlinear response characteristic.

The measured spectra had sufficient SNR and spectral resolution to verify an instrumental nonlinearity level of around 1%. In the future, if this type of instrument is made with a smaller instrumental nonlinearity, it will be of interest to increase the SNR and to increase the spectral resolution of the measurement. These goals can be addressed by using a higher modulation frequency within the frequency response of the detector being measured. The use of higher modulation frequencies would have two beneficial effects. First, the noise contribution to the spectra would be smaller, because most detectors have a noise power spectrum that decreases to a plateau value at frequencies beyond the $1/f$ corner frequency. Second, the fixed bandwidth of the spectrum analyzer would be a smaller fraction of the frequency. This would make the width of the fundamental more narrow, and make smaller second-harmonic components easier to measure, because they would no longer fall as close to the shoulder of the fundamental component.

5 Conclusions

Feasibility of a scanned-fringe spatial-harmonic-distortion test was demonstrated at a wavelength of 10.6 μm. For the single-detector characterizations performed, the minimum measurable nonlinearity was shown to be less than 1%, which represents a factor of 3 better sensitivity than previously reported. Because this nonlinearity does not change within the range of irradiances measured, we postulate that this 1% level represents instrumental nonlinearity rather than detector nonlinearity, which typically increases with increased detector-plane irradiance. The repeatibility was approximately 0.1% of the fundamental.

The advantages of this technique include the measurement of nonlinearities down to the 1% level, the ability to measure nonlinearity as a function of spatial or temporal frequency, and the use of harmonic distortion as a convenient summary measure for detector nonlinearity.

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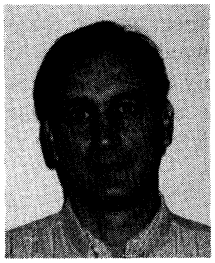

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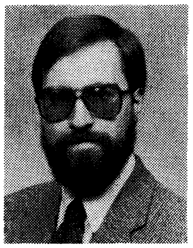

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