Synthetic-array heterodyne detection: a single-element detector acts as an array

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Received June 10, 1994

A simple technique, synthetic-array heterodyne detection, permits an ordinary single-element optical detector to behave as though it were a coherent array. A successful experimental implementation of a synthetic two-pixel array, using a CO_2 laser and a single-element HgCdTe photodiode is reported. A different heterodyne local oscillator frequency is incident upon each resolvable region of the detector surface. Thus different regions are mapped to different heterodyne beat frequencies. One can determine where the photons struck the detector surface even though a single electrical connection to the detector is used. This also prevents the destructive interference that occurs when multiple speckles are imaged (akin to spatial diversity). In coherent lidar this permits a larger field of view. An acousto-optic modulator produces the local oscillator frequencies and can achieve good spatial separation of optical frequencies of the order of a megahertz apart.

Imaging is frequently based on arrays of individual elements, such as a CCD array, or on a storage medium whose surface is serially poled, such as a Vidicon. I have devised a scheme that permits an ordinary single-element detector to act as if its surface were divided into an array of separate detector elements. That is, as required for any multielement detector, one can determine the region on the surface where the photon struck. All synthetic-array elements are read out continuously and in parallel over the single electrical connection. I have experimentally realized a two-element synthetic array on a single-element detector.

Coherent optical heterodyne detection is well known[1]: an incoming signal source combined with a coherent reference frequency, called the local oscillator (LO), results in a beat at the difference frequency on a (square-law) detector. There are two principal advantages: First, the detector has gain because the electrical signal is proportional to the electric field of the optical signal multiplied by the electric field of the intense LO. Second, background light can be effectively removed because the optical frequency of the signal source can be resolved electronically, relative to the LO optical frequency, to the linewidth of the laser. Near-shot-noise-limited operation is common.

There are two distinct reasons why one might want an array detector. The first is self-evident: simply to have multiple channel detection such as for imaging. The second is to provide a means of spatially integrating the signal in heterodyne detection, such as might be done for spatial diversity reception.[2] The reason this cannot be done directly on a single large element is that heterodyne detection is phase sensitive and so its efficiency is degraded when the LO and signal wave fronts are not spatially matched. Light scattered from any optically rough surface (i.e., not a mirror) or propagated through a turbulent atmosphere contains speckle, which is a random assortment of phase fronts.[3,4] Furthermore, large collection optics used to capture the signal may also introduce phase distortions in the wave front.

In the presence of mixed optical phase fronts, the square-law detector produces a sum of mixed phasors at the difference frequency, which tend to interfere destructively. For Gaussian speckle the resultant signal power distribution is a decaying exponential whose mean and standard deviation are equal to the average power.[3] The upper bound of the signal-to-noise ratio of detected power is limited to unity by the speckle fluctuations. Unlike direct energy detection, mixed phase fronts cannot be spatially integrated. Heterodyne detection is a better tool for measuring frequency shifts and time delays than signal amplitude.[4]

One route to spatial averaging has been through an array of separate detector elements.[2,5–7] Assuming that the adjacent speckle amplitudes are uncorrelated, the signal-to-noise ratio cap rises to the square root of the number of array elements.[3,6] A serious drawback to use of this array is that its outputs must be separately amplified and detected. Even when one is simply interested in the integrated signal (and not in the image) the outputs must be in parallel because the signal is ac and cannot be integrated on the chip (e.g., like a CCD array). By contrast, the synthetic array is attractive because only a single output need be processed.

The synthetic-array concept is illustrated in Fig. 1. The surface of the detector is illuminated with a set of discrete optical frequencies spatially spread out like a rainbow. This replaces the usual single-frequency LO. This is combined with the (single-frequency) signal on the detector. Now in place of a single beat frequency there will be many. Because the LO optical frequency at each region on the detector is distinct from its neighbors, the resulting beat frequency between it and the signal is also distinct. Consequently one can determine from what spot on the surface of the detector a given beat frequency signal arose; that is, where the

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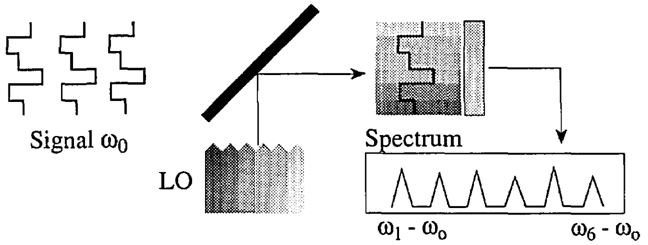

Fig. 1. Synthetic-array concept: the LO is composed of multiple frequencies ($\omega_1, \ldots$) that are spatially distinct on the detector. The signal is single frequency with a distorted phase front. Mixing by the detector gives a difference-frequency spectrum. Each frequency maps to a different spatial location on the detector.

photons struck. Moreover, since different regions of the detector produce different frequencies there is no longer any stationary destructive interference, and so the speckles can be summed (as simply as integrating the rectified signal). The key is not just the use of a multiple-frequency LO but that these frequencies are spatially distinct.

This process increases the electrical bandwidth that the detector must sustain. If the spacing between LO frequencies is large, one may exceed the available detector bandwidth. With typical optical frequencies and subgigahertz bandwidth detectors, the key technical hurdle is the creation of a well-dispersed rainbow whose bandwidth is $\sim 10^{-5}$ to 10^{-6} (or less if possible) of the optical frequency. The angular dispersion must exceed the natural laser beam divergence for the each frequency to become spatially distinct. An ordinary diffraction grating has insufficient dispersion, and separate generation with multiple laser sources is extravagant, except perhaps with laser diodes.

We simultaneously create the rainbow frequency set and the required dispersion with an acousto-optic modulator (A.O.M.). An attractive future method could use a spatial light modulator to generate a spread of optical sidebands; at present the devices are slow, but their speeds are improving.

I have implemented a single-element detector that behaves as a synthetic two-element detector as follows (see Fig. 2). A cw waveguide CO_2 laser (Synrad 48G) running on the 10.6-μm line (P20) was spatially filtered, then put through a traveling-wave A.O.M. (NEOS germanium) to shift its frequency. The beam was not focused into the modulator but instead was collimated to 3.5 mm in diameter (FWHM Gaussian). The modulator was driven with less than 0.1 W of rf power at two separate frequencies, 25 and 29 MHz. The A.O.M. output beam contains two new wavelengths, 10.6 μm upshifted by 25 MHz and 10.6 μm upshifted by 29 MHz, which deviate from the input beam by 46 and 54 mrad, respectively. These beams were separately recognizable on liquid-crystal thermal paper. Because of the beams' angular dispersion, the 25-MHz-shifted light was focused slightly to the side though partly overlapping the 29-MHz-shifted light on the surface of the unbiased photovoltaic HgCdTe detector. These formed the LO reference beam. The signal source was a tiny fraction of the unshifted 10.6-μm light split off before the modulator. This too filled the detector surface.

There were thus four electrical frequencies present on the detector: the dc level of the combined light (dominated by the LO beam), a 4-MHz beat that was due to the residual spatial overlap between the 25- and 29-MHz-shifted light, a 25-MHz beat that was due to the left half of the signal and 25-MHz-shifted light, and a similar 29-MHz beat from the right half of the signal. The signal was sampled and its Fourier transform taken directly on the digital oscilloscope. The 4-MHz signal was a useful diagnostic for aligning the two reference frequencies onto the small detector element.

To demonstrate the position-sensitive detection I blocked either the left or right half of the 10.6-μm signal beam and observed a drop in the 25- or 29-MHz signal, respectively. I observed an extinction ratio in excess of 10 when blocking either side. In other words, the 2-pixel device could image the blockage position, thus acting as an array.

Slow fluctuations (over minutes) of the detected signal amplitudes were observed at each of the difference frequencies. I attribute the fluctuation to interference from residual leakage of the unshifted beam through the modulator. The leakage is aligned with the LO so that is mixes efficiently. This is not an intrinsic problem (e.g., two high-frequency modulators used differentially would both increase the dispersion and eliminate this difficulty as well as any rf pickup).

One has three degrees of freedom in focusing the LO onto the detector. For the case in which the detector is in the focal plane, the spot location is determined solely by the angle of incidence of the LO on the focusing lens. The spot size is determined by the waist at the lens. The mean wave-front k vector at the focus is determined by the point of incidence on the lens. The first two degrees of freedom determine the spot resolution, whereas the last two determine the LO/signal phase front overlap that affects the heterodyne efficiency. I do not address optimization of the heterodyne efficiency here.

At the focal length f of the lens before the detector, the light is spread out transversely according to its angular components (see Fig. 3). Two beams, corresponding to two different frequency components, deviating by an angle $d\theta$ are displaced (to first order) in the focal plane by an amount $dh \cong f d\theta$. As noted above, the position in the focal plane is independent of the spatial overlap of the input beams. If w_i is the waist of a collimated beam on the lens, then the focal waist is $w_f = 4f\lambda/\pi w_i$. For illustra-

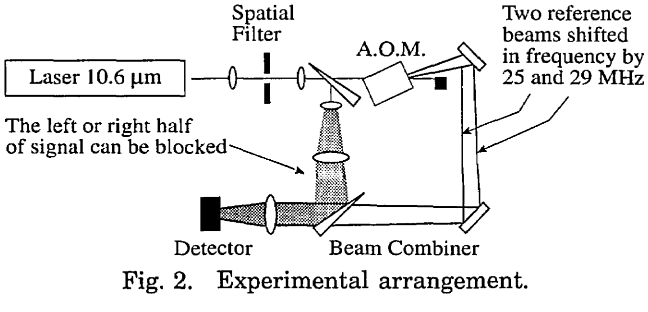

Fig. 2. Experimental arrangement.

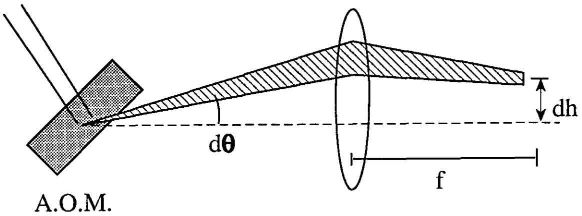

Fig. 3. Focusing onto the detector: the displacement in focal plane is determined by the angle of deflection. The focal plane spot size is determined by the beam diameter (and divergence).

tion, if $\lambda = 10.6\ \mu\text{m}$, $w_i = 5$ mm, $f = 10$ mm, and $d\theta = 2.7$ mrad, then $dh = 27\ \mu\text{m}$ and $w_f = 27\ \mu\text{m}$.

I shall say a frequency is spatially resolvable from another when the separation exceeds the spot size: $dh > w_f$. The corresponding minimum frequency separation is $d\nu_{\min} = k d\theta_{\min} = 4k\lambda/\pi w_i$, where k is the effective modulator dispersion rate. Both the focal spot size and the separation scale with f, so their ratio, and thus the effective resolution, is independent of the focal length. For illustration, if $k = 0.54$ MHz/mrad, then $d\nu_{\min} = 1.46$ MHz is the minimum frequency spacing for a 5-mm waist of a 10-μm wavelength beam. One can increase w_i independently of $d\theta$ by expanding the beam before the modulator and thereby increase the frequency resolution. Enlarging the beams after the A.O.M. will not increase the frequency resolution.

The synthetic array has three drawbacks not present in a real multiple-element detector array. First, instead of multiple small detectors one has a single large-area detector and consequently a greater capacitance. While this may ultimately limit the total array size, the limit may be so large as not to matter; even a 0.25-mm^2 HgMnTe photovoltaic detector typically has a bandwidth in excess of 50 MHz. Second, if one intends to resolve the synthetic-array elements (i.e., use it in an imaging mode), then the LO shot noise from all the channels appears in each channel. A similar increase in shot noise occurs in Fourier-transform spectroscopy. Third, if one instead integrates over the synthetic pixel magnitudes (i.e., uses it in a spatial averaging mode), then the noise bandwidth is increased by the number of pixels. Since speckle often dominates the noise (presumably why one desires to spatially average), this may not be a serious defect.

The picture that I have painted using pure frequencies is oversimplified. The laser was not a single-mode laser and most likely had hundreds of megahertz of bandwidth. However, the difference frequency can be narrower than the laser linewidth of even a single mode (in fact it was narrower than our 50-kHz spectrometer resolution). Even though the modes do interfere with each other and can reduce the signal level depending on the path-length difference between the signal and reference beam, this does demonstrate that a narrow-band beat can be obtained from a broadband laser. While a single-mode laser would be preferable it was not an issue for this experiment.

Although this demonstration used only two frequency channels, clearly more can be inserted. The total number of channels possible from a single modulator is determined by the bandwidth of the modulator divided by the channel spacing. Although the manufacturer's stated 3-dB response point for this modulator was ±2.5 MHz at 27 MHz, we have seen effective modulation out beyond ±10 MHz. Thus this A.O.M. is theoretically capable of using 14 array channels spanning ~0.38 mm linearly on the detector. We note that at visible wavelengths typical detectors have ~10 times faster rise time and the focal waist can be 10 times smaller, permitting orders-of-magnitude denser and larger arrays than in the mid-IR.

There is a practical note in driving the A.O.M. with more than two frequencies. Because the limiting feature of the modulator is peak voltage and not average power, the relative phases of the electrical driving frequencies can be set so as to minimize their periodic constructive interference (e.g., a mode-locked pulse).

The synthetic array permits new detection modes. For example, one could dynamically change the heterodyne gain on each synthetic element individually simply by boosting the power in that frequency channel at the A.O.M. driver. As a second example, one can dynamically change the pixel sizes, number, and positions, adapting to differing speckle sizes or tracking a moving target.

A virtue of this scheme is simplicity. The experimental apparatus to create a synthetic array is only slightly more complex than ordinary single-element heterodyne detection: a multiple-frequency synthesizer substitutes for a single-frequency generator. The scheme has but a single connection, is inherently parallel, and requires only a single amplifier. In contrast, a physical array requires parallel access with separate wiring, amplifiers, and processing for each element, which may become prohibitive as the array size increases.

It appears feasible to use a second acousto-optic modulator at right angles to create a two-dimensional rainbow. Fast spatial light modulators would provide an even simpler approach to a two-dimensional array.

I thank R. Sander, G. Busch, and J. Tiee for suggestions and C. Simmons for assistance.

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