Measurements of Speckle Fields with a Multimode Local Oscillator

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Abstract

We investigate the improvement in target detection that can be achieved by the use of multiple local oscillators in a coherent laser radar system. Experiments at a laser wavelength of 1.55 microns used a target with a rough surface that produced a speckle pattern on the receiver. Four separate heterodyne channels were implemented using the four elements of an InGaAs quadrant detector. Combination of the information in these four channels was found to give significant improvements in target detection probability.

Keywords: Heterodyne detection. Coherent laser radar.

Introduction

Coherent laser radar (lidar) systems are based on mixing the field received from a laser illuminated target with a local oscillator field. The resulting interference process provides significant advantages in sensitivity compared with direct detection techniques. The nature of the interference process is such that only transverse fields of identical form (i.e. non-orthogonal fields) produce an interference signal. In conventional systems the local oscillator takes the form of a TEM_{00} Hermite-Gaussian beam from a laser source. This has the disadvantage that only the TEM_{00} mode component of the speckle field is detected. This is the root of a number of shortcomings in the performance of coherent laser radar systems. These include: (i) reduced detection sensitivity – all higher order spatial mode content remains undetected, (ii) inability to scale the receiver aperture, and hence, the signal-to-noise – conventionally the aperture diameter is chosen to match the diameter of a lobe in the speckle field, (iii) significant signal fluctuation – as a single speckle lobe moves across the receiver aperture the fundamental mode content, and the total energy in the received field, shows large variations.

In previous years' work on this project, we investigated the improvements that could be gained from accessing higher-order mode content, and built an experimental system which resolved the received field into a series of waveguide modes [1], [2]. By measuring the power in each mode, in a serial fashion, we were able to investigate the improvement which could potentially be gained for a typical speckled target return. In order to realise this improvement it is necessary to access all the modes simultaneously, i.e. in a parallel fashion. In the present paper we present the results of experiments which capture heterodyne lidar signals from four spatially orthogonal local oscillators simultaneously. Our previous experimental work used a CO_2 laser at 10.6µm wavelength. The work reported here used a semiconductor diode laser operating at 1.55µm; this is a wavelength that has been of increasing interest for lidar systems: it has low atmospheric attenuation and is compatible with off-the-shelf telecoms components.

Generation of multiple local oscillators

A 2D multi-mode interference (MMI) waveguide beam-splitter was designed to provide four spatially orthogonal local oscillator fields; one for each element of an InGaAs quadrant detector (EOS model IGA –020–QUAD/1MHz). This configuration provided a means of coherently detecting four spatially orthogonal components of a speckle field simultaneously. The MMI splitter was realised in hollow silicon waveguide technology [3]. This involves mask generation, photolithography and the use of deep reactive ion etching (DRIE) techniques to form accurate square-section hollow channels in the surfaces of silicon wafers. In practice the hollow waveguide width and depth were chosen to be 125μm. For 1.55 μm operation with this multimode guide width, the predicted splitting length for a 2x2 splitter was 15,121 μm. Accordingly, a silicon hollow waveguide chip containing 125μm wide hollow waveguides was cut to this length. In conjunction with an upper lid section, the appropriate square cross-section hollow waveguide was formed. In the experimental measurements, the ~9 μm diameter TEM_{00} output field from the fibre-coupled laser source was allowed to diffract from the fibre and then collimated. This was achieved using a microscope objective lens at an appropriate distance from the fibre tip. A second microscope objective lens provided a ~30 μm ($1/e^2$) diameter beam-waist, which was launched along the axis of the hollow silicon guide. The field emerging from the exit of the guide was analysed by using a microscope objective to produce a magnified image on a vidicon camera. Following accurate alignment of the chip with the input beam, both 2 x 2 and 3 x 3 way (using a shorter MMI device) TEM_{00} array fields were demonstrated. Figure 1 illustrates an example of each.

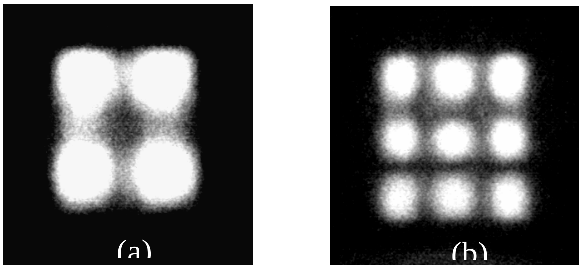

Figure 1 *Experimental measurement of a (a) 2x2 way splitting function, and, (b) 3x3 way splitting function, both provided by a 125μm square copper-coated hollow silicon waveguide at a wavelength of 1.55 μm. The waveguide was 15.1 mm long for (a) and 13.4mm long for (b).*

Experimental setup

The experimental setup used for assessing the multiple spatial mode local oscillator concept is shown in figure 2.

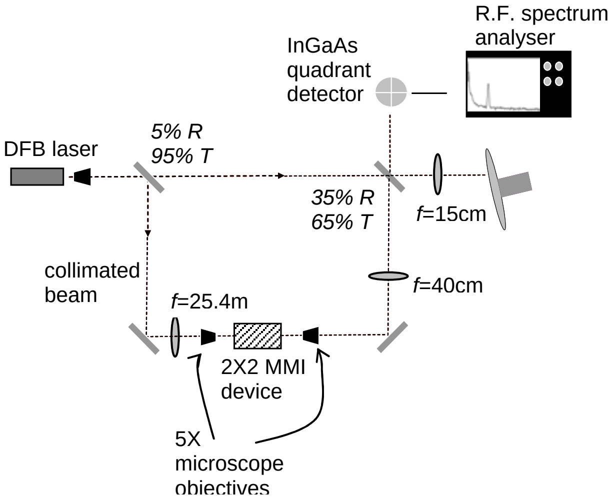

Figure 2 *Experimental setup*

The laser source was a 1.55 μm DFB laser. The target was a rotating disc with a rough surface which produces a time-varying speckle pattern back at the receiver. Part of the laser output was focussed on to the target, the remainder was split off and coupled into the MMI device to produce the local oscillator array. The rotating disk target was angled to produce a Doppler-shifted return signal; thus the heterodyne electrical signal from the detector elements oscillates at the Doppler frequency, which was ~8kHz. The beam diameter before the 15cm focal-length lens was matched to the individual local oscillator lobe size. Thus, with the target placed in the focal plane of the lens, the characteristic size of the speckle pattern at the receiver was equal to the size of the local oscillator, which facilitates a high heterodyne efficiency. The inclusion of neutral density filters in the illuminating beam path allowed data to be captured with various signal to noise levels. The output signals from the quadrant detector were digitised at a sampling rate of 250Ks/sec and streamed to hard disk for off-line processing. Typical data sets consisted of 1 second long time series, which could be subdivided into segments to generate a number of individual power spectra.

Results

The aim of the experiment was to investigate improvements in the ability to detect the presence of the target by using the signal from four channels instead of the more usual single channel. The detection process operated by setting a threshold level in the power spectrum and identifying when the spectral peak produced by the Doppler-shifted light scattered from the target exceeds the threshold. Owing to the statistical nature of the speckle and additive noise fluctuations, it is desirable to have many spectra for each signal-to-noise ratio (SNR) so that a detection probability can be computed accurately. To this end, each 1 second long data set was divided into 500 segments each of 2 milliseconds duration. A separate spectrum was calculated for each segment. An additional algorithm, described below, was used to combine the data from the four channels after their spectra had been computed. A sample spectrum from one channel and for one segment of time series data is shown in figure 3. The peak occurs at ~ 8 kHz, corresponding to the target Doppler shift. The dotted line indicates a threshold level. Note that some spectral bins have been set to zero to avoid a spurious noise spike (due to electrical pick-up) near 16 kHz and low-frequency noise below 1 kHz.

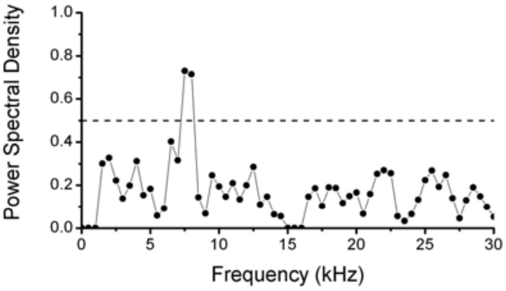

Figure 3 *a sample spectrum from single channel, calculated from a 2ms time segment via a discrete Fourier transform.*

The threshold level was set by using a data-set in which the illumination beam was blocked, i.e. noise alone: the threshold was adjusted upwards until no spectral bins within the 0-30kHz band crossed the threshold in any of the 500 spectra. The same threshold was used for the other data-sets and the detection probability was calculated as the number of times the spectral peak produced by the target exceeded the threshold divided by the total number of spectra.

The processing using all four channels was the same, except that each spectrum was an average of the four separate spectra produced from the different channels; this averaging reduces the fluctuations in both the signal and the noise. The threshold in this case was set using all four channels of the noise-alone data set. With the experimental configuration described above, in conjunction with the data acquisition and post-processing system, values of detection probability as a function of signal levels could be obtained. A plot of detection probability versus SNR is shown in figure 4. The SNR used is that for the single channel; the channels were well-matched, so the same SNR applies to each. The noise value used was the noise in the entire 30kHz bandwidth shown in figure 3, computed from the noise-alone data set.

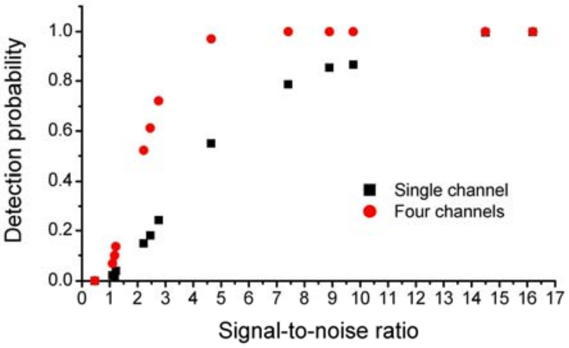

Figure 4 *Detection probability as a function of signal-to-noise ratio.*

Discussion and Conclusions

The use of four channels gives a higher detection probability for SNR values between 15 and 1. This corresponds to conditions of very strong signal and virtually no signal respectively. The benefit is obvious, with a factor of three or more increase in detection probability over the lower range of SNR values. Another interpretation is that a given detection probability can be achieved at lower SNRs and thus lower laser powers (SNR is directly proportional to laser power). So for a required detection probability of 0.8, the gain of a 4 channel system over a single channel system is a reduction in 'acceptable' SNR from 7.5 (8.8 dB) to around 3.5 (5.4 dB): a significant performance improvement for a real-world lidar system. In fact, for some applications (e.g. a scanning obstacle-avoidance lidar) our experiment under-estimates the improvement in detection probability. This is because in our experiment the rotation of the target wheel, which is necessary to provide the Doppler shift, causes the speckle to vary rapidly. This means that even the 2ms duration spectrum "averages" over a number of speckle fluctuations (a few in this case). In a real-world system the Doppler shift would arise from pure line-of-sight motion and the speckle field would not change greatly during the detection process; the resulting larger fluctuations would produce a lower detection probability for a single channel and thus a greater improvement when 4 (or more) spectra from independent channels are averaged together.

The improvements demonstrated above could have a significant impact in enabling lidar systems to detect, identify and track targets in clutter and at long ranges. In practice, the degree of improvement predicted and demonstrated experimentally could improve both the range and all-weather performance of any coherent lidar system. Alternatively it would facilitate significant reductions in the laser power (and hence size, weight, pump energy and cooling) required to achieve any given range performance compared with conventional systems. More channels are feasible with further improvements in detection probability predicted.

References

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