Measurements of Speckle Fields with a Multimode Local Oscillator

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Abstract

Measurements of the heterodyne signal in the higher order spatial mode components of a speckle field have been made with a local oscillator that can be tuned through a series of orthogonal spatial modes. The measurements indicate that the higher order components have significant levels of heterodyne signal associated with them. If these individual components could be combined, this could generate valuable increases in overall signal level. This could lead to improved range performance in coherent laser radar receivers or the ability to substantially reduce transmitter power for a given range requirement.

Keywords: Heterodyne detection. Coherent laser radar.

Introduction

Coherent laser radar 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, and (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 early work, the possibility of making more comprehensive measurement of the field returned from a laser illuminated target with a local oscillator which produces a range of orthogonal transverse modes, was proposed and demonstrated for simple mirror targets [1].

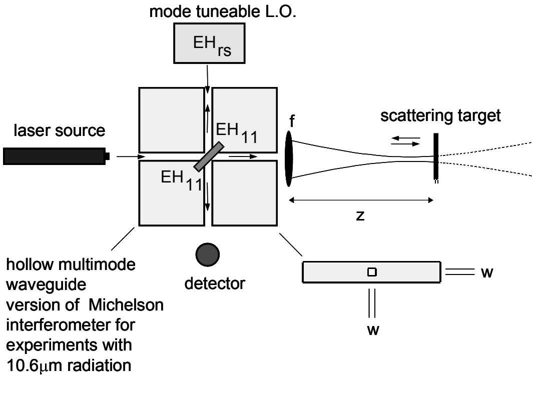

Figure 1: Schematic of multimode mode local oscillator measurement concept

In the earlier work a hollow multimode waveguide based version of the Michelson interferometer was used to provide the source for target illumination and to mix the field returned from the target with the output from the local oscillator. The local oscillator produced a set of modes of the hollow multimode waveguide.

More recently the application of the concept to the detection of speckle fields associated with laser radar receivers has been addressed from a theoretical standpoint [2]. For the experimental scenario illustrated in figure 1, theoretical predictions indicate that the heterodyne signal has its largest magnitude for the fundamental (EH_{11}) waveguide mode. However, significant heterodyne signal levels are also present in a range of higher order modes, particularly those of order EH_{p1} and EH_{1q}. Depending on the exact nature of the illuminating regime, the theoretical calculations led to the conclusion that the addition of 9 local oscillator modes can increase the cumulative heterodyne efficiency by a factor of five. In practice the overall improvement in system performance will depend on what the system is measuring e.g. the presence or absence of a target, a target Doppler shift or a vibration frequency. The absolute improvement in signal magnitude will also be dictated by the manner in which the separate electrical signals are processed and combined. The impact of measurement noise also needs to be taken into account. Even so, significant signal-to-noise benefits should be feasible with the approach. With this in mind, in this paper we set out to corroborate the theoretical predictions by making measurements of the heterodyne signal levels associated with the higher order spatial mode components of a speckle field.

Mode Tuneable Local Oscillator

The work requires the use of a local oscillator that can be tuned through a suitable set of modes of the square cross-section hollow waveguides that the interferometer is based on. The concept for the waveguide mode tuneable local oscillator evolved from the well-known ray-optic model of waveguide mode propagation. In addition to providing an intuitive way of understanding waveguide mode propagation, this simple model also provides us with a means for generating waveguide modes of different order within a multimode waveguide. In principle all we have to do is arrange for four plane waves with appropriate tilts and phase offsets between them to be produced at the entrance aperture of a multimode waveguide.

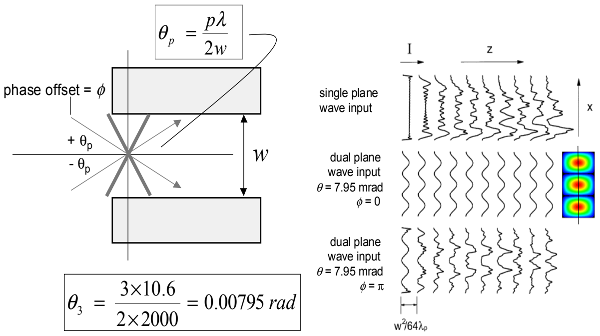

Figure 2. Schematic illustrating the concept of generating waveguide modes by the appropriate superposition of plane-waves

The validity of this concept is clarified in figure 2 in relation to the generation of the third order mode of a planar (1D) step index waveguide. Where the guide width, w = 2.0 mm, the wavelength of the radiation, λ = 10.6 μm, and, the mode order, p = 3. The expression $\theta_p = p\lambda/2w$ gives the angle of the plane wave field associated with the mode as 7.95 mrad. The inset in figure 2 illustrates the transverse intensity profiles produced as a result of the injection of: (top) a single plane wave input beam with a tilt of + 7.95 mrad; (middle) two plane wave input beams with tilts ± 7.95 mrad, and, with *zero* phase difference between them; (bottom) two plane wave input beams with tilts ± 7.95 mrad but with π radians phase difference between them. Figure 2 highlights the fact that two beams with appropriate tilts *and phase offsets* are required to generate any desired mode.

A mode tuneable local oscillator device was realised on the aforementioned basis. In practice it *also* took the form of a multimode waveguide version of the Michelson interferometer. This served the purpose of allowing a fundamental mode input field to be split in two and then recombined. The recombination process followed the application of suitable tilts. These were achieved via plane mirrors located in electronically controllable mounts placed at the ends of the waveguide interferometer arms. One of the mirrors was also mounted on a piezoelectric transducer in order that appropriate phase offsets could be achieved between the fields returned to the beam splitter.

In practice the mode tuneable local oscillator is only an approximation to the ray-optic model because the optical fields upon which the appropriate tilts and phase offsets are imposed, are not plane waves, as in the idealised case of figure 2, but fundamental (EH_{11}) waveguide mode fields. This has the effect that the resulting modes are not pure. Furthermore, because we have limited ourselves to the use of only two quasi-plane-wave beams, only modes of order EH_{p1} and EH_{1q} can be generated. Nevertheless, this is still a very effective starting point for the proof-of-principle experiments that have been proposed.

We now turn our attention to the practical implementation and use of the complete field analyser. As discussed and illustrated in figure 3 this takes the form of two concatenated hollow waveguide Michelson interferometer structures. These were based on 2.0 mm wide square cross-section hollow waveguides machined into a polycrystalline alumina substrate. The substrate also included alignment slots for two 50%/50% beam splitters. A lid is attached to the substrate forming the upper walls of all the waveguides. Two gimbal mounts hold plane mirrors at the ends of the arms of the interferometer that is used to generate the waveguide modes. One of the mirrors was mounted on a piezo-electric transducer. This allowed a linear axial phase shift to be imposed.

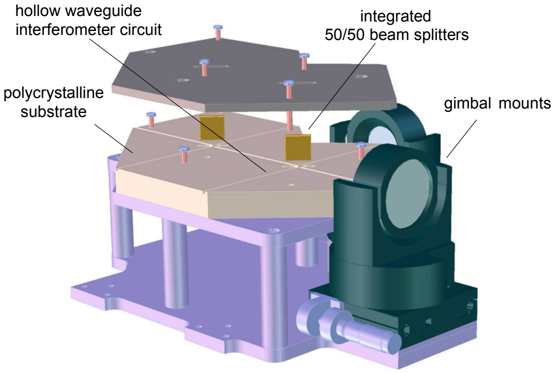

Figure 3. Illustration of the speckle field analyser incorporating a local oscillator which could be tuned through a series of waveguide modes

Experimental Measurements and Results

As illustrated in figure 4, for the experimental measurements the speckle field analyser was used in conjunction with a CO_2 laser source, a spinning disk target, a Cadmium-Mercury-Telluride detector, and, a spectrum analyser. The waist size of the TEM_{00} input from the CO_2 laser source was chosen to provide efficient excitation of the fundamental EH_{11} mode of the input hollow waveguide. At the first 50%/50% beam splitter the input field splits in two. The transmitted portion goes on to illuminate the scattering target, whereas the reflected portion acts as the source for the mode tuneable local oscillator.

Light which is back-scattered from the

surface of the target is coupled into the hollow waveguide interferometer exciting a spectrum of waveguide modes. Here it is mixed with the local oscillator field. Depending on the settings of the mode tuneable local oscillator this takes the form of a specific EH_{pq} waveguide mode.

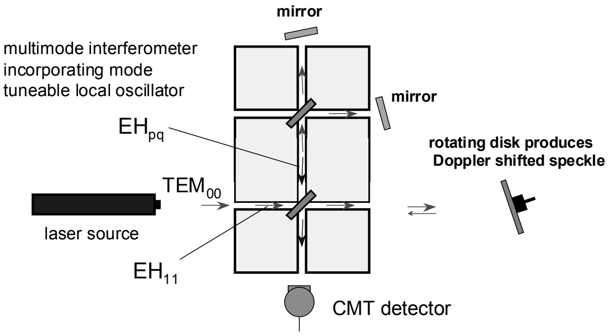

Figure 4. Experimental configuration

For these measurements, the focussing lens shown in figure 1 was omitted so that uncertainties in focal length would not lead to uncertainties in the theoretical curves. In this configuration the speckle pattern produced at the entrance to the waveguide by light backscattered from the rough target surface has a characteristic speckle size that is smallest when the target is closest to the waveguide. As the target is moved away from the waveguide the speckle size increases until it attains a maximum size which is of the order of the waveguide dimensions. In this experimental configuration the full range of speckle size variations can be investigated by moving the target out to a distance of 50cm from the waveguide. The significance of the speckle size lies in its relation to the modal content that the backscattered field excites in the waveguide: a smaller speckle size means that a greater fraction of the available power lies, on average, in higher order modes. When the speckle size is on the order of the waveguide dimensions the target is in the far field and the higher order mode content is least.

The rotation of the target and its angular inclination with respect to the illuminating beam results in a Doppler shift of the back-scattered light. In mixing with the local oscillator field a heterodyne beat signal is thus produced. The frequency of the signal can be controlled by the rotation speed of the target. Beat frequencies of a few kilohertz were used for the experimental measurements. The rotation of the target also produces a time varying speckle pattern on the receiver aperture. With the integration time on the RF spectrum analyser appropriately set, this allowed a time averaged power spectrum to be produced. A typical spectrum analyser output is shown in figure 5.

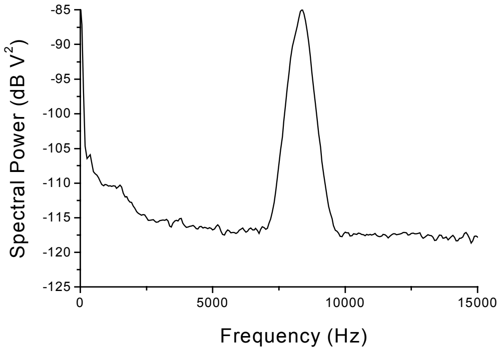

Figure 5. Typical RF spectrum analyser output characteristic

This is for the case in which a fundamental EH_{11} mode was used as the local oscillator. Note the logarithmic scale on the vertical axis. The centre frequency of approximately 8kHz is determined by the angle and rotation speed of the target and is chosen to avoid the higher noise levels below 5kHz. The average power in each local oscillator mode is proportional to the area under the peak in the spectrum.

This quantity is plotted in figures 6(a), (b) and (c), with the mode tuneable local oscillator set to generate the modes EH_{11}, EH_{12} and EH_{13} respectively. The solid lines in the figures are the results of theoretical predictions using the methods discussed in a previous paper[2].

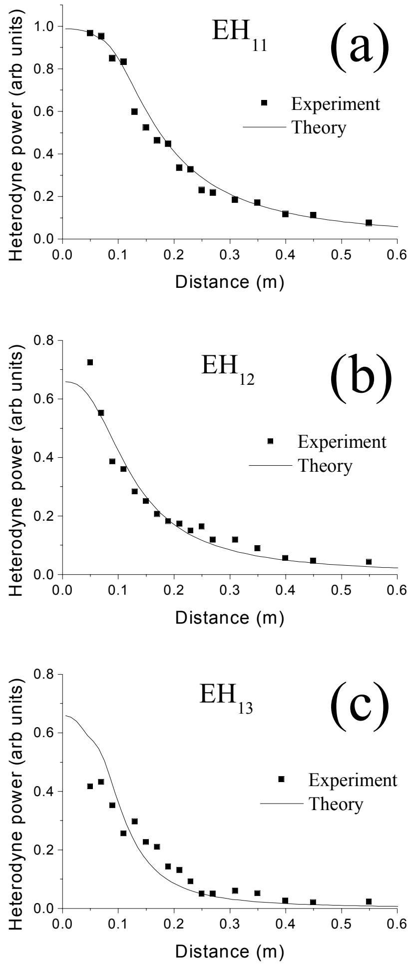

Figure 6. Measurements and predictions of heterodyne power as a function of target distance for three different settings of the mode tuneable local oscillator

All the plots in figure 6 indicate good agreement between experiment and theory. The data were normalised to the value of the average power in the EH$_{11}$ mode at the closest position to the waveguide; no other parameter fitting was carried out. The decreasing heterodyne signal power level as a function increasing distance of the target is due to the reduction in the laser power entering the waveguide from the, approximately Lambertian, target backscatter: this has, essentially, a 1/z^2 dependence. Although the magnitude of the signal produced with the local oscillator set to generate the fundamental (EH$_{11}$) is always the greatest, as illustrated in figures 6b and 6c, significant signal levels are also produced for higher order local oscillator modes, even in the far field. Note that these same power levels will also be available in the EH$_{21}$, and EH$_{31}$ modes, as well as smaller amounts in the EH$_{23}$, EH$_{32}$, EH$_{22}$ and EH$_{33}$ modes. If these individual components could be combined, this could generate valuable increases in overall signal level. This could lead to improved range performance in coherent laser radar receivers or the ability to substantially reduce transmitter power for a given range requirement. Techniques for achieving this end result will be addressed in the next phase of the work.

References

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