Optimising backscatter from multiple beam interference

LAURA O'DONNELL, MILES J. PADGETT, AND STEVEN D. JOHNSON*

School of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, UK
*steven.johnson@glasgow.ac.uk

Abstract: Optical sensing applications are usually reliant on the intensity of the measured signal. For remote sensing applications where a target is probed with a laser beam, the sensitivity will be limited by the amount of backscattered light returned from the target to the detector. We demonstrate a method of increasing the signal returned to the detector by illuminating the target with a number of independently controlled beams, where both the position and phase are optimised. We show an improvement in the backscattered signal that is proportional to the number of beams used. The method is demonstrated within a laser microphone, measuring audio signal due to vibrations in surfaces, showing a significant improvement in the signal-to-noise of the measurement.

1.   Introduction

Imaging and sensing applications are often limited in range when used in real-world situations. For remote sensing techniques that rely on the detection of backscattered light, the main limitation is a lack of signal due to random scattering of light from rough surfaces such as walls, roads, or people. By shaping the wavefront of the light incident on the scattering surface, it is possible to control the resultant light field, and thus, control the speckle pattern. Following the seminal work by Vellekoop and Mosk [1], many groups worldwide have gone on to apply this technique in a variety of ways [2–4], predominantly for focusing light through a scattering medium. While techniques do exist for focusing light reflected from a scattering surface [5], they typically require prior access to the medium in order to characterise the reflection matrix of the surface.

Here, we demonstrate a method which uses the coherent combination of speckle backscatter from several beams to significantly increase the signal-to-noise of a reflected signal from a scattering surface. The optimisation of backscattered light is achieved by projecting a series of beams onto the scattering surface and optimising each beam's position and phase. This two-step optimisation process ensures that the individual speckle pattern produced from each beam constructively interferes to a maximum at the detector. The control of beam position and phase has been well studied within the field of holographic optical tweezers [6–8], allowing our method to be easily implemented with pre-existing techniques. Our method can be applied to any scattering material and assumes no prior knowledge of the scattering material involved, allowing remote optimisation.

The speckle produced from scattered light has been shown to be an invaluable metrology tool that has previously been utilised to measure laser wavelength [9,10], non-line-of-sight movement [11] and sound [12–15]. In this paper, we demonstrate a possible application of our technique: improving the signal-to-noise ratio of a laser microphone. Laser microphones can be used to listen at a distance by measuring acoustic vibrations transferred to a surface. Previous work [12] has shown that by observing lateral shifts in speckle patterns, sound signals can be extracted.
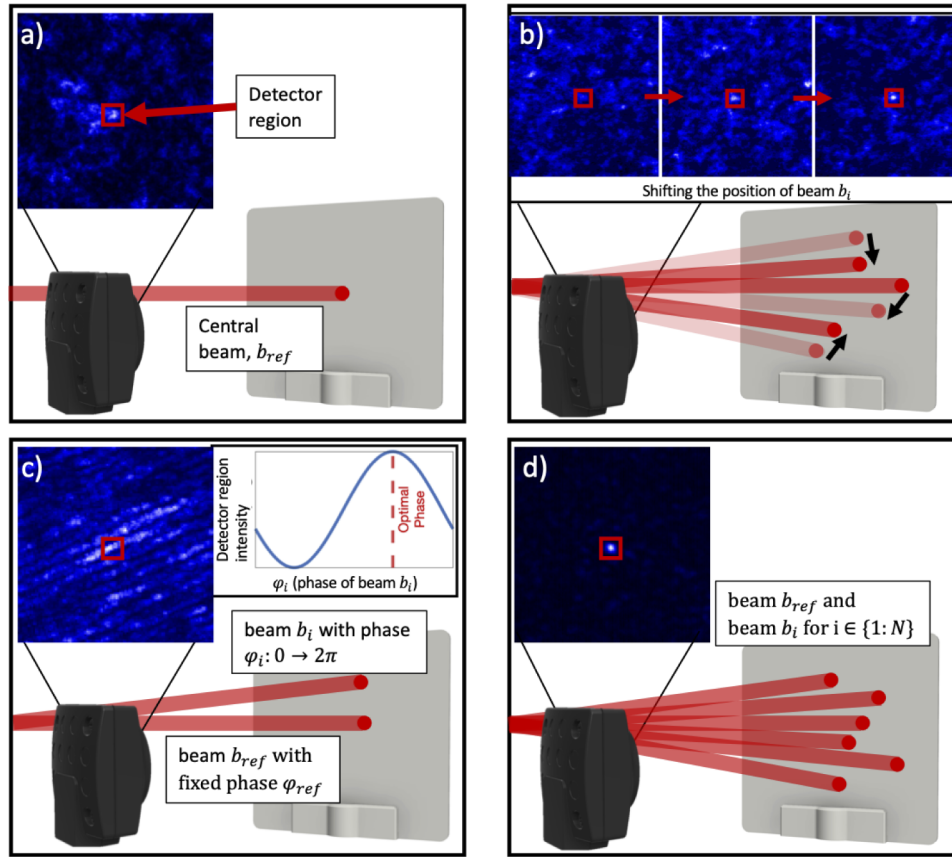
Fig. 1. Illustration of optimisation method. (a) A single reference beam, b_{ref}, is projected onto the scattering surface, ensuring a bright speckle lies in the detector region to optimise. (b) Position optimisation: each additional beam, b_i, is scanned in position to ensure there is sufficient signal at the detector region for constructive interference. (c) Phase optimisation: each additional beam, b_i, is projected at its optimised position alongside b_{ref}. Beam b_{ref} is kept constant in phase while the phase of b_i is scanned between 0 and 2π with the optimal phase being stored. (d) The reference beam along with all N additional beams at their optimised position and phases are projected and a maximum is observed at the detector.

The proposed backscatter optimisation technique could be used with nanophotonic phased arrays, which are able to perform beam steering and control of the beam phase via a silicon-based structure [16–18]. With the recent development of these devices fast and compact beam control can be performed with relatively high laser powers.

2. Optimisation method

An individual beam incident on a scattering surface will create a speckle pattern, with the size of the speckle grains determined by the beam diameter, laser wavelength and distance from the scattering surface [19]. The proposed method, as illustrated in Fig. 1, uses a number of individual beams projected at different points on the scattering medium, with each beam producing a unique speckle pattern at the detector. To achieve an increased intensity at our detector, we require the ability to shift both the position and phase of these projected beams. Initially, we determine the position on the scattering surface for a single reference beam, ensuring a bright speckle lies at

the detector region we wish to optimise. Typically, the size of the region is chosen to match the size of the speckle. The speckle size is determined by the beam diameter, and the interference fringe distance is determined by the spot spacing. For a stable system is required that the speckle be larger than the interference, hence a larger spot separation in comparison to beam size. In addition, the laser coherence length must also be large enough for there to be strong interference over the distance of the spot separation.

A specified number of beams N are projected randomly about the central reference beam. Due to the non-uniformity of the scattering medium, each of the beams produce speckle patterns uncorrelated with respect to each other. To achieve a signal maximum at the detector, we have to ensure that there is some overlap with the detector region and the speckles in these patterns. This is done by micro-scanning the position of each beam on the scattering surface in one dimension in order to maximise the light at the detector. Then, to optimise the phase and thus ensure constructive interference, we project both the reference beam and one of the N additional beams at the optimised position found previously. The reference beam is kept at a fixed phase while the phase of the additional beam is cycled from 0 to 2π. As the phase is scanned, a sinusoidal relationship between the beam's phase and the detector signal is observed. The optimal phase, the peak of this sinusoidal intensity response, is stored. This position and phase optimisation process is then repeated for each of the N additional beams.

3. Experimental methodology

3.1. Experimental setup

As a proof of principle, we demonstrate our optimisation method using a laser combined with a spatial light modulator (SLM) to generate independent beams on the scattering surface. Constructing a single blazed grating on the SLM creates a single beam and with the addition of multiple blazed gratings we can project a series of beams onto the scattering surface, each with a tuneable position and phase. The multiple gratings are shown over the whole SLM with the gratings generated and summed with modulo 2π to produce the grating for display. This has the disadvantage that amplitude modulation (a technique which involves shifting unwanted light within the hologram into the reflected order) must be employed to suppress "ghost spots", which arise because a phase-only SLM was used [20], although more complex schemes of beam generation can produce more efficient phase pattern construction [21,22]. Amplitude modulation results in light being lost from the modulated first order and this loss is monitored using a photodetector. Figure 2 shows the experimental set-up. A helium-neon laser ($\lambda = 632.8$ nm) is expanded to fill a phase-only SLM (Holoeye Pluto, 1920×1080 pixels) that shapes the wavefront of the beam. The first order from the SLM is selected using an iris and focused onto a beamsplitter. This beamsplitter directs part of the light to a photodetector (Thorlabs PDA100A-C), which is used for alignment purposes. Measuring the ratio of light intensity measured on the photodetector and on the camera enables a direct feedback to gauge the enhancement for the system optimisation. The Fourier plane (i.e. far field) of the SLM is imaged onto the scattering surface. The scattering material used is the common paint pigment titanium oxide powder (TiO_2), chosen as it is a highly scattering material, which is mixed with clear glue and secured between two thin microscope slides. Primarily, a CMOS camera (Thorlabs DCC1645C) is used as the detector, where a small array of pixels are summed together to act as a single detector. For our measurements, a 5×5 pixel array was used with an area of approximately 20 μm^2. In our demonstration, the camera is typically placed 30 cm from the scattering surface. For our experimental parameters, our projected beam size is approximately 20 μm in diameter, with the N additional beams lying at random positions within a range of 1.5 mm of the central reference beam. During position optimisation, each additional beam is shifted a distance of approximately 30 μm 20 times, giving a total position optimisation range of approximately 0.6 mm. Typically, each position/phase measurement takes 0.6 s, with the limiting factor being the synchronisation between the SLM

refresh rate and the camera's frame rate. For the data in this paper, we sample 12 points of the sine curve in our phase optimisation step, although this number can be reduced by using discrete Fourier transforms. With 12 phase and 20 position measurements, the total optimisation of 10 beams takes approximately 3 minutes. However, the use of alternative technologies such as digital micromirror devices (DMDs), which can operate at 20 kHz, could drastically reduce this optimisation time.
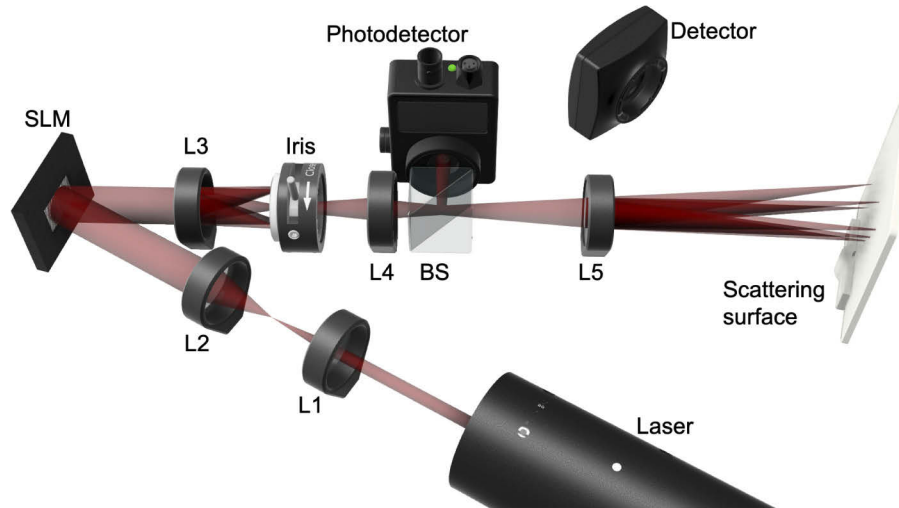

Fig. 2. A schematic of the optimisation system. The laser beam is expanded to fill the screen of the SLM, and additional orders are filtered out with an iris acting as a pinhole. The scattering surface is in the far field of the SLM where the numerous beams are located. A detector (either a camera or a photomultiplier tube) measures the backscattered signal. By displaying multiple grating patterns on the SLM, we can produce individual beams which can be adjusted independently in position and phase to maximise the signal measured by the detector.

3.2. Enhancement results

To determine the enhancement in the backscattered signal at the detector, the optimisation method was performed with a varying number of beams N with 10 runs being taken for each N value. Each run was performed with a random set of initial positions for each of these N beams. The intensity enhancement is defined as the ratio between the optimised region intensity and the average intensity in the rest of the speckle pattern. As shown in Fig. 3, the enhancement initially follows a linear trend, although trails off at higher beam numbers. This is due to slow changes in the speckle pattern over time meaning that for larger N, and thus longer optimisation, complete constructive interference was harder to achieve. For surfaces with a strong absorption there will be faster decorrelation of the speckle due to heating of the surface, in which case synchronising a fast SLM and detector will enable efficient optimisation to be performed.
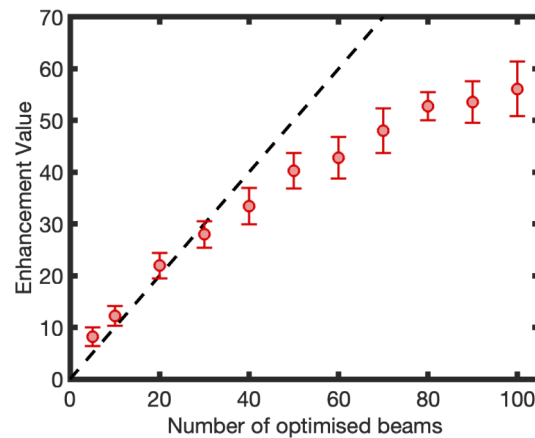
Fig. 3. The intensity enhancement versus number of optimised beams. The error bars represent the standard deviation of the enhancement measured over 10 optimisation runs. The dotted line indicates a linear relationship with the enhancement equal to the number of beams.

4. Laser microphone application

To demonstrate our backscatter optimisation method, we apply our technique to a laser microphone experiment. The setup in Fig. 2 is modified with the scattering medium changed to a nitrile sheet stretched over a mount and positioned in front of a loudspeaker. The flexible membrane has a much larger movement than the microscope slides, allowing very small acoustic signals to be recorded. It was found that the optimum surface for this meausurement was a flexible membrane, with stiffer materials there would be insufficient movement due to acoustic vibration for the meausurement to be performed. The reflected signal at the incident angle normal to the surface was not used and instead an area of speckle was optimised for coherent backscatter.

As the camera has insufficient bandwidth to measure audio frequencies (15 frames per second at full resolution), it is replaced with a photomultiplier tube (PMT, Thorlabs PMM02-1, bandwidth 0-20 kHz). To reproduce the 5×5 pixel detector region on the camera optimised previously, a 20 μm diameter pinhole is placed in front of the PMT. Using this setup, the optimisation is performed via the same method as described in section 2. Following this optimisation, we create a stationary reference for our system by unblocking the first order (previously blocked by the iris) and projecting it onto a stationary part of the mount, this acts as a mixing of the signal with a local oscillator. This results in interference fringes within our speckle pattern, and by monitoring the shift of these fringes within our detector region we can extract sound. To ensure the most sensitive microphone, we universally shift the phase of all the first order optimised beams between 0 and 2π and choose their phase such that the optimised region lies on the steepest slope of the sinusoidal curve.

The spectrogram in Fig. 4 shows a linear frequency chirp (1000 to 100 Hz) and the corresponding signal measured by our detector using an optimised system with 30 beams. Frequencies above 1000 Hz were above the natural frequencies of the target and showed very little response. We take two measurements, one on a fully optimised system and another on a system optimised in position but with a randomised phase. From Fig. 4, it is clear that the phase optimisation step of our method is vital for constructive interference to occur and leads to an enhanced laser microphone signal. Our fully optimised system also reveals the harmonics of our linear chirp, occurring in the acoustic signal due to large surface movements, as well as peaks at 120 Hz, 240 Hz and 480 Hz, which are harmonics of the SLM refresh rate of 60 Hz. There will be

a strong correlation for the effectiveness of with microphone due to the natural frequencies present in the vibrating surface. This is seen in both the optimised and unoptimized cases. An analysis of the spectrogram data shows that where our microphone has the best signal-to-noise (around 300 Hz), the fully optimised system achieved a signal-to-noise ratio 30 times greater than the non-optimised system. For a single measurement, the oscillation amplitude was 50 time greater than the noise floor, therefore was can determine a minimum sensitivity of 6 nm could be measured over a 1 second integration, based on one oscillation being a half-wavelength wavelength of longitudinal movement.
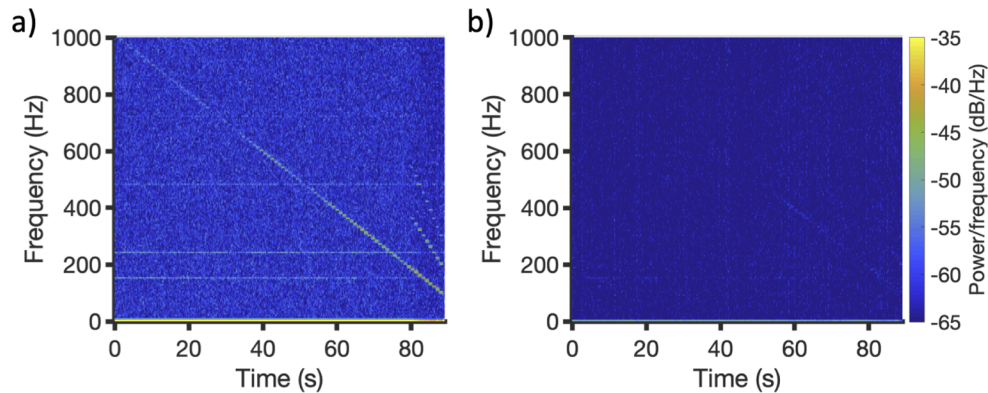

Fig. 4. Spectrogram plots of sound recovery from our laser microphone setup. A linear chirp ranging from 1000 to 100 Hz is played through the loudspeaker and the Fourier transform of the intensity signal from the PMT is plotted for (a) 30 beams with optimised position and phase and (b) the same 30 beams with optimised position and randomised phase.

5. Conclusion

We have demonstrated a method for enhancing backscattered light, showing that by manipulating the position and phase of a number of beams on a scattering surface we can optimise backscatter to a maximum at a detector. The optimised enhancement increases with the number of beams used. The method was demonstrated with a laser microphone where audible frequencies up to 1000 Hz were measured. In contrast, a system optimised in position only was unable to resolve such frequencies. The method of optimising pixels individually on an SLM has previously show enhancements of 1000 for some materials [1], what we have demonstrated here is that with far fewer phase controllable elements enhancement can also be performed in reflection. The transfer matrix method for reflection [5] can produce higher enhancement with the trade-off of requiring a large number of measurements (16000 measurements). We believe this method will have many applications in imaging, gas sensing, and other tasks where access to the scattering medium is not always possible. With the current development of nanophotonic phased arrays, our use of discrete beams would allow this technique to be implemented with a high-power laser (surpassing power limit of currently available commercial SLMs) within a phased array source. This increase in optical power could be utilised to enable a significant increase in the range capabilities for remote sensing systems.

Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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