Interferometry from a scattering medium

Z. Wang, A. M. Weiner, and K. J. Webb*

School of Electrical and Computer Engineering, Purdue University, 465 Northwestern Avenue, West Lafayette, Indiana 47907, USA

**Corresponding author: webb@purdue.edu*

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A two-beam random interferometer is demonstrated where coupling is facilitated by a scattering medium. A modulation observed in the normalized second-order intensity frequency correlation of the transmitted light is attributed to the relative temporal delay of the two beams and is insensitive to beam alignment and spacing. © 2007 Optical Society of America

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There is a broad interest in imaging using light in tissue, for example, by means of optical diffusion tomography [1] and in imaging through scattering material. In a range of situations, including astronomy and wireless communications, the presence of random media usually leads to a deterioration of the signal. On the other hand, recent research on communication through a random medium suggests that the random scattering of coherent electromagnetic waves may enhance the amount of information that can be transmitted when multiple transmitters and receivers are used [2]. We introduce an intensity interferometer that provides information about two signals incident on a scattering medium. The approach uses second-order intensity correlations over frequency that has previously been used to characterize slab scattering media [3] and the bandwidth of a multimode optical fiber [4]. The two coherent beams, which are not necessarily overlapping, interfere in a scattering medium. We find that a transmission measurement of speckle intensity in a small spot, measured with a detector array (a CCD camera in our case), allows information about the input beams to be recovered. In this case we demonstrate two identical beams, in which one is delayed relative to the other, and we find a sinusoidal modulation in the second-order intensity correlation with laser scan frequency that can be related to the relative delay of the two incident beams.

Figure 1 shows our experimental setup. The framed Michelson interferometer with a 50:50 beam splitter produces the relative time delay in the two beams incident on the random scattering medium. The two arms provide path lengths of S_1 and S_2. The interferometer may be aligned to provide either spatially overlapped collinear output beams, as in a standard Michelson interferometer, or spatially displaced output beams (by tilting mirror M2 in Fig. 1). The spatial filter controls the speckle size for satisfactory imaging with a CCD camera, and linearly polarized light with the same polarization as the input beams is measured. We used a highly coherent, frequency-tunable laser diode (New Focus Vortex 6017, operating at 850 nm) as our light source. This external cavity laser diode offers frequency scanning up to ~80 GHz with a narrow linewidth (~5 MHz) and single mode output. The Fabry–Perot interferometer was used to monitor the laser frequency during scanning. As the laser frequency is scanned, a series of intensity speckle patterns were captured by the CCD camera and downloaded to the computer for data processing. The scattering samples used in the experiment were commercial white acrylics (Cyro Industries, Acrylite FF) with the scatterers composed of small TiO_2 particles of average diameter approximately 50 nm. Samples with reduced scattering coefficients (from a diffusion model [1]) of $\mu_s'=14\ \mathrm{cm}^{-1}$ (corresponding to a transport mean free path of 0.07 cm) and $\mu_s'=4\ \mathrm{cm}^{-1}$ (with a mean free path of 0.25 cm) were used.

Under the weak scatter assumption, where the average distance between scattering events is large relative to the wavelength, and with a sufficient number of scattering events, the first-order field statistics are zero-mean circular complex Gaussian [5]. The normalized second-order intensity correlation can thus be written as [3]

$$\langle \tilde{I}(\nu+\Delta\nu)\tilde{I}(\nu)\rangle = |P(\Delta\nu)|^2, \tag{1}$$

where $\langle I\rangle$ is the mean intensity, $\tilde{I}=(I-\langle I\rangle)/\langle I\rangle$ is a normalized intensity, used for mathematical convenience, and $P(\Delta\nu)$ is the Fourier transform of the ensemble averaged intensity temporal impulse of the scattering medium $p(t)$. Throughout, we assume a normalization $\int p(t)\mathrm{d}t=1$.

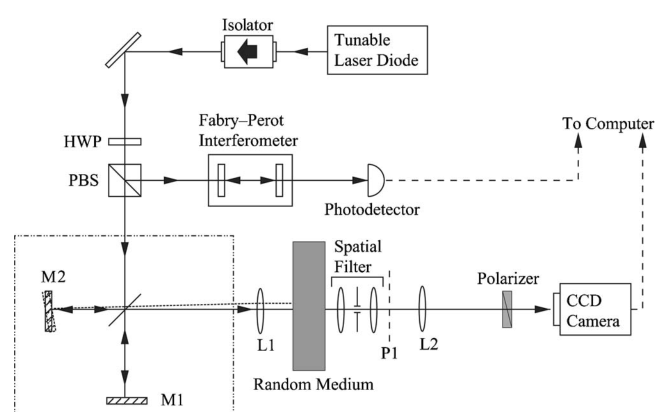

Fig. 1. Two-beam random medium interferometer experimental setup.

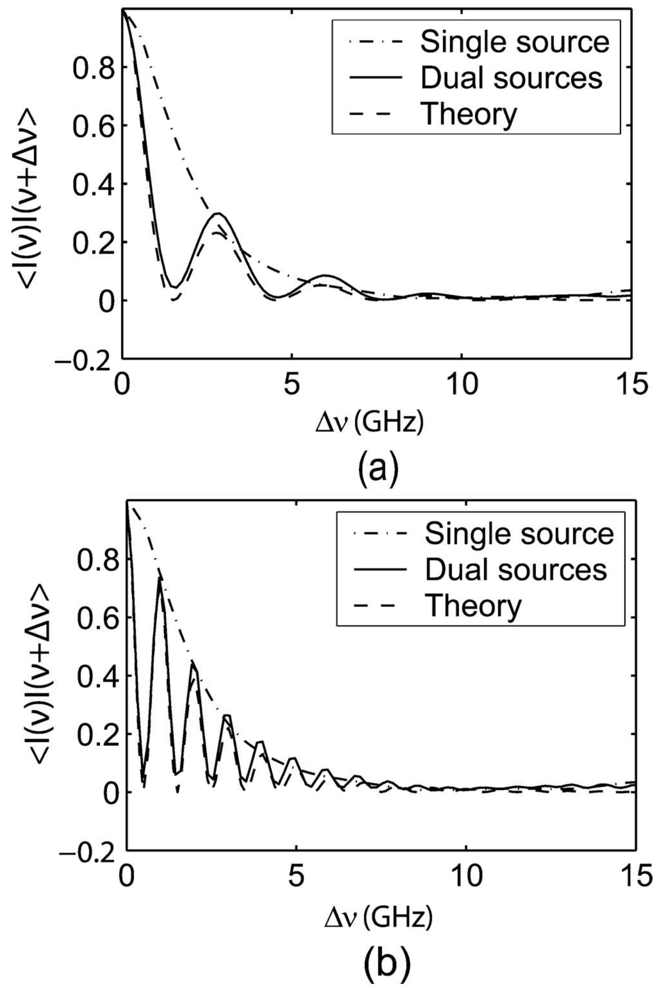

Fig. 2. Second-order frequency intensity correlation measurement (solid curves) for two coincident input beams having (a) $|S_1 - S_2| = 5$ cm and (b) $|S_1 - S_2| = 14$ cm. The dotted–dashed curve shows the case for a single beam, and the dashed curve shows the result from a diffusion equation model. The sample thickness is 6 mm, and $\mu_s' = 14\ \mathrm{cm}^{-1}$.

The Michelson interferometer in Fig. 1 produces two equal-amplitude beams with a relative delay of $\delta t = 2|S_1 - S_2|/c$, with c as the vacuum light speed, due to the length difference in the two arms (having lengths S_1 and S_2). By scanning the laser frequency, $|P(\Delta\nu)|$ due to the superposition of two excitation pulses, where one is delayed by δt relative to the other, can be obtained. Assuming coincident (or symmetric with respect to the detector) optical beams,

$$p(t) = \frac{1}{2} p_0(t) + \frac{1}{2} p_0(t - \delta t), \tag{2}$$

where $p_0(t)$ is the impulse response with a particular source location (input beam position) and detector location (small spot captured by the CCD camera). The second-order intensity correlation now becomes

$$\langle \tilde{I}(\nu + \Delta\nu) \tilde{I}(\nu) \rangle = |P_0(\Delta\nu)|^2 \cos^2(\pi \Delta\nu \delta t), \tag{3}$$

where $P_0(\Delta\nu)$ is the Fourier transform of $p_0(t)$. Therefore, the identical and delayed pulses produce a sinusoidal-type modulation of the second-order intensity correlation for a single input beam. From Eq. (3), the modulation period $\delta\nu$ of the second-order correlation is

$$\delta\nu = \frac{1}{\delta t} = \frac{c}{2|S_1 - S_2|}, \tag{4}$$

which allows $|S_1 - S_2|$ to be measured. Of importance, the scattering medium allows for large beam separation. In the more general case of spatially separated input beams with an asymmetric detector location, or when the two beams are not identical, the detector provides a measure of

$$p(t) = w p_1(t) + (1 - w) p_2(t - \delta t), \tag{5}$$

where $p_1(t)$ and $p_2(t)$ correspond to the normalized temporal impulse responses with a single beam illuminating the respective excitation points, and w (with $0 \leqslant w \leqslant 1$) provides the relative weight according to the excitation energy.

Figure 2 shows the measured second-order frequency correlations for $|S_1 - S_2|$ are 5 and 14 cm and with coincident excitation beam spots for a scattering sample having $\mu_s' = 14\ \mathrm{cm}^{-1}$ and a thickness of 6 mm. We have also plotted the single source measurement result, which forms the modulation envelope for the ripple due to $|S_1 - S_2| \neq 0$, as described by Eq. (4). As the path-length difference increases, the modulation period in the second-order intensity correlation decreases, as Eq. (3) suggests.

Figure 3 shows the second-order intensity frequency correlation measured for two different scattering medium thicknesses, 9 and 12 mm, both with $\mu_s' = 4\ \mathrm{cm}^{-1}$. In both cases, the path-length difference was set to 8 cm. The more rapid decay with frequency for the case with more scatter (12 mm) is evident. This occurs because the thicker sample induces a greater spread in the photon transit times [wider $p_0(t)$], which implies narrower $|P_0(\Delta\nu)|$. Also clear is that the modulation has the same period, because both measurements have input beams with $|S_1 - S_2| = 8$ cm.

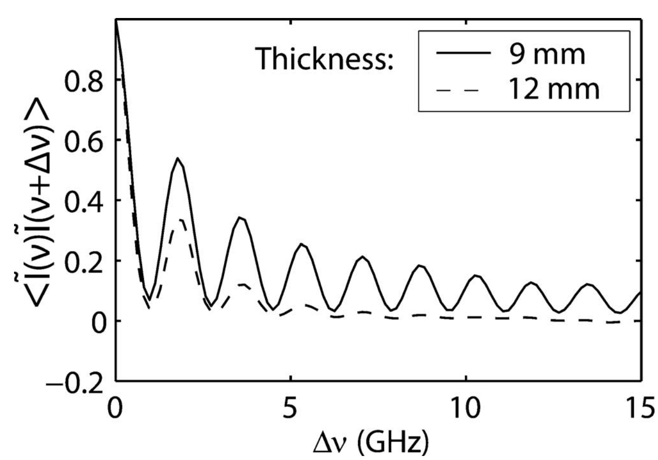

Fig. 3. Second-order frequency correlations measured for two samples having $\mu_s' = 4\ \mathrm{cm}^{-1}$ and a thickness of 9 mm (solid curve) or 12 mm (dashed curve). $|S_1 - S_2| = 8$ cm.

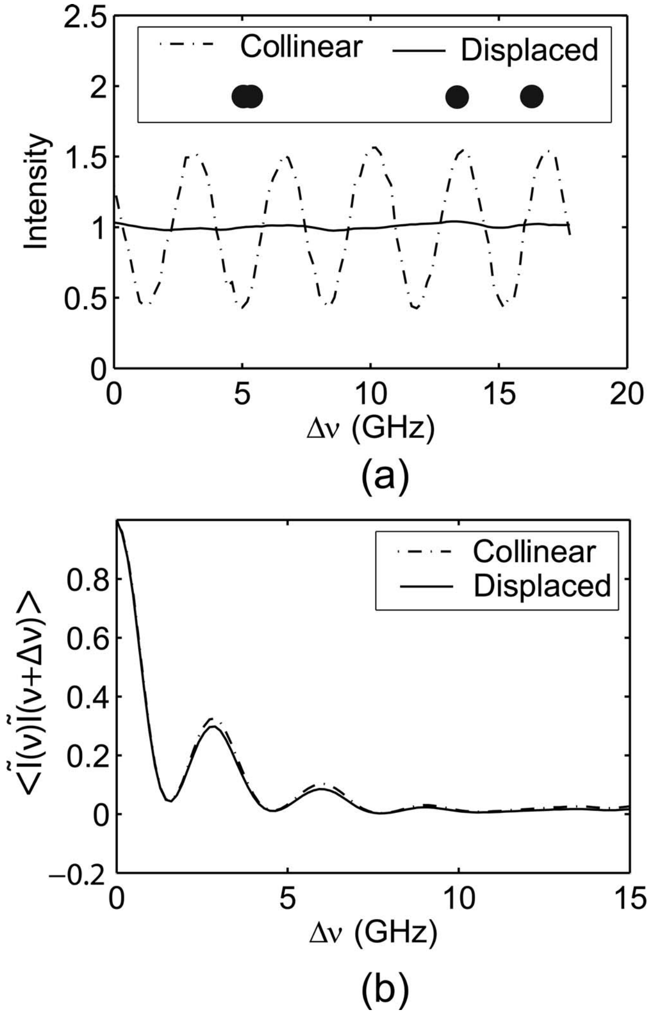

Fig. 4. (a) Measured average transmitted intensity with coincident and spatially separated input beams. (b) Measured second-order correlation. The sample had $\mu_s' = 4\ \mathrm{cm}^{-1}$ and a thickness of 9 mm, and $|S_1 - S_2| = 8$ cm.

To illustrate the impact of beam alignment, Fig. 4(a) gives the measured average power transmitted through the scattering medium as a function of scan frequency for coincident input beams and with beams having a separation of 4 mm, in both cases with $|S_1 - S_2| = 8$ cm. For reference, the spot has a radius of ~1 mm. As expected, strong spectral fringes in the average power are observed in the collinear condition, but these fringes disappear quickly when the beams are separated. The measured normalized second-order intensity correlations for these same two cases, where the sources are symmetric with respect to the detector, given in Fig. 4(b), are virtually identical. This highlights a fundamental difference between our random, second-order intensity correlation interferometer and the standard optical interferometer configuration. The frequency-dependence of the total intensity due to differing phase in the two input beams is removed in the normalized correlation of Eq. (3). Moreover, any laser power variation with scan frequency is also removed in the same normalization process. In practice, one may intentionally offset the two beams slightly, breaking the collinear condition. This results in the interferometric intensity changing less with frequency, thereby reducing any normalization problems, especially for a CCD camera with a limited dynamic range at a specific exposure time.

The intensity interferometer we present should be contrasted with that of Hanbury-Brown and Twiss, where a temporal correlation of two spatially separated intensity measurements can be used to infer source phase information [6]. In this Letter, the speckle pattern intensity frequency correlation is related to the magnitude of the Fourier transform of the ensemble impulse response for the scattering medium, and hence the modulation reflects the superposition of the two random medium excitation pulses. Our results are distinct from the modulation in the Fourier transform of the detected signal with a superposition of two pulses (and no scattering medium), which is known as the Alford and Gold effect [7]. In the Alford–Gold effect, a modulation in the spectrum is obtained when two beams are superimposed on a photodetector, provided that their delay difference exceeds the optical coherence time. In contrast, in this Letter, speckle patterns are observed when two beams from a narrow-linewidth laser are superimposed on a scattering medium. The coherence time of the laser significantly exceeds the delay difference, which is opposite to the requirement for an observation of the Alford–Gold effect. Also, a second-order correlation of the electric field obtained with a reference measurement with that from an imaging measurement has been proposed as a means of imaging through scattering media [8], a different strategy from our determination of intensity correlations over frequency with simultaneously applied sources.

The two-beam random medium interferometer provides a simple way to retrieve relative path-length information from the second-order intensity correlation over frequency, with identical input beams and a symmetrical detector. For the nonsymmetric case, we expect the modulation depth will be reduced.

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