Characterization and imaging in optically scattering media by use of laser speckle and a variable-coherence source

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We demonstrate the application of laser-speckle statistics formed by a variable-coherence source illuminating a scattering medium, for determining the scattering parameter μ_s' of a diffusion model for the medium. Furthermore, we apply this technique to visualize laterally localized inhomogeneities embedded within a highly scattering sample.

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Laser-speckle statistics were previously used to perform measurements of surface roughness for a variety of materials, by use of both speckle contrast measurements and speckle pattern correlation.[1–3] Recently it was shown that the scattering parameters of optically diffuse media can be determined by measurement of speckle contrast in a transmission geometry as the material thickness is varied.[4] We also demonstrated the use of speckle contrast measurements, with a simultaneously scanned source–detector pair, for detection of inhomogeneities in thick optically scattering samples. The sensitivity of the speckle statistics to the coherence length of the laser, relative either to the surface roughness[1–3] or to the variance in the photon path-length distribution within a volume,[4,5] provides a basis for these measurements that does not require any motion of the scattering medium. Another class of laser-speckle measurements depends on the motion of the scatterers, as has been done in imaging retinal blood flow[6] and determining changes in vascular flow velocity.[7] In these studies[1–7] a light source of fixed coherence was used. Here we demonstrate the use of a variable-coherence laser source to determine material scattering parameters and to detect inhomogeneities within an optically scattering volume through laser-speckle statistics, without varying the material thickness or scanning the source or detector and without depending on motion of the scattering medium.

The experimental setup is shown in Fig. 1. Our key idea is to synthesize a variable-coherence source by frequency modulating a tunable laser diode at a rate much faster than the integration time of the detector. A frequency-modulated cw dye laser was previously used to generate low-coherence light for ballistic imaging in scattering media.[8] Our laser source is a commercially available external-cavity diode laser centered at 850 nm, with an unmodulated linewidth specified to be approximately 5 MHz. The laser's center frequency can be tuned over a range of many gigahertz by application of a modulating voltage to the cavity end mirror, which is mounted upon a piezoelectric translator. The translator is modulated by a 200-Hz variable-amplitude voltage ramp, whose period is much shorter than the CCD integration time. Therefore the collected speckle data result from the time integration over multiple frequency scans, and the effective laser spectrum is the time-integrated spectrum over the modulation period. These effective spectra were characterized with a scanning Fabry–Perot etalon and have an approximately rectangular line shape resulting from the linear ramp modulation for the piezoelectric translator. The laser output is spatially filtered and then focused by lens L1 onto the front surface of our samples, which are a series of commercial white acrylics with scattering that is due to TiO_2 particles suspended in an acrylic background. An image spot approximately 1 mm × 0.8 mm in size on the back surface of the sample is magnified by a factor of 15 and imaged onto a 1000 × 800 pixel, cooled Princeton Instruments CCD array by lens L2. The aperture at L2 provides control over the speckle size at the CCD array, ensuring adequate resolution with the 15-μm CCD pixel size, while allowing a sufficient number of speckle spots for well-developed intensity statistics.

The intensity statistics of a speckle pattern can be described by the contrast ratio σ_I/μ_I, where σ_I is the standard deviation and μ_I is the mean.[4] The contrast ratio for a source with power spectral density $S(\lambda)$ is[4]

$$\frac{\sigma_I}{\mu_I} = \frac{[\int\int_0^\infty S(\lambda_1)S(\lambda_2)F(\lambda_1,\lambda_2)\mathrm{d}\lambda_1\mathrm{d}\lambda_2]^{1/2}}{\int_0^\infty S(\lambda)\mathrm{d}\lambda}, \tag{1}$$

where

$$F(\lambda_1,\lambda_2) = \left|\int_0^\infty p(L)\exp\left[-j2\pi L\left(\frac{1}{\lambda_1}-\frac{1}{\lambda_2}\right)\right]\mathrm{d}L\right|^2 . \tag{2}$$

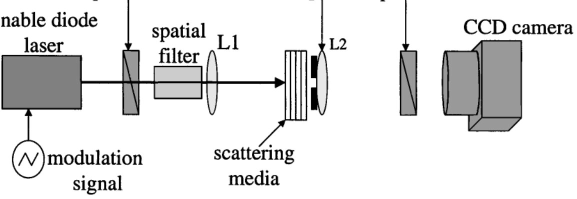

Fig. 1. Laser-speckle experimental setup for the material characterization experiments.

In Eq. (2), $p(L)$ is the path-length distribution for the travel of photons through the scattering medium. We use a diffusion equation model for a slab[9] of thickness d, with scattering coefficient μ_s' [in inverse centimeters (cm^{-1})] and absorption coefficient μ_a (in cm^{-1}) to describe $p(L)$.[4]

We measured the dependence of the speckle contrast ratio on the source linewidth for 2 different materials and for 16 different source linewidths, with the results shown in Fig. 2. For a fixed amount of scatter, the speckle contrast decreases rapidly with decreasing coherence length when the coherence length is comparable with the spread in $p(L)$. For two different thicknesses of the same material, the contrast ratio decreases more rapidly for the thicker material as the linewidth is increased because there is more scatter. To determine a value for μ_s' we performed theoretical fits to the contrast-ratio data in Fig. 2 by numerically implementing Eq. (1) with rectangular $S(\lambda)$ and by varying μ_s' with $\mu_a = 0$ (since the plastics have negligible absorption at the wavelength of interest). For the heavily scattering material a value of $\mu_s' = 12.5\ \mathrm{cm}^{-1}$ was obtained, which resulted in good agreement between the theory and the experimental data for both thicknesses. A value of $\mu_s' = 6\ \mathrm{cm}^{-1}$ was determined for the less-scattering material.

The heavily scattering plastic in Fig. 2, was previously characterized by use of speckle data obtained from a 632.8-nm He–Ne laser with a fixed ≈1-GHz linewidth by variation of the material thickness,[4] yielding $\mu_s' = 40\ \mathrm{cm}^{-1} \pm 5\ \mathrm{cm}^{-1}$. The difference from the present value of $\mu_s' = 12.5\ \mathrm{cm}^{-1}$, obtained with the 850-nm laser, can be very well explained by the wavelength-dependent (Rayleigh) scattering cross section,[10] which has a λ^{-4} dependence.

We can also use the speckle contrast ratio, together with a variable-linewidth source, to visualize laterally localized inhomogeneities within optically scattering media. To demonstrate this we fabricated the sample shown in Fig. 3, which consists of five sheets of the less-scattering acrylic ($\mu_s' = 6\ \mathrm{cm}^{-1}$), each 3 mm thick, as the background. We milled a 5-mm-diameter hole through the center of the central sheet to form or locate an inhomogeneity. The imaging optics were modified such that an area of 45 mm × 36 mm on the back face of the sample was imaged onto the CCD array, and we also adjusted the aperture at L2 to give a large number of sufficiently sized speckles in the speckle pattern.

Speckle patterns were obtained for two different inhomogeneities, a void and a 5-mm-diameter disk of heavily scattering acrylic, and for a homogeneous sample, for laser linewidths of 5 MHz and 17 GHz. The contrast ratio was calculated locally within a 150 × 150 pixel subregion, and we then scanned this subregion throughout the speckle pattern in 25-pixel increments to form a map of the contrast ratio within the speckle pattern domain. The contrast-ratio map obtained from a homogeneous sample of the background material for each laser linewidth was then substracted, leaving the contrast-ratio difference images shown in Fig. 4. In these images red represents a higher contrast ratio than in the homogeneous case, and blue represents a lower contrast ratio.

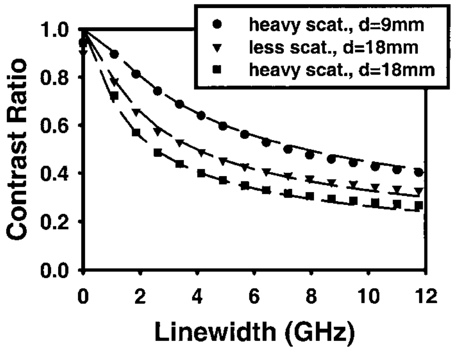

Fig. 2. Contrast-ratio data as a function of laser linewidth for two different acrylics. Symbols, experimental data; dashed curves, theoretical fits. The top and bottom curves are for the heavily scattering acrylic with $\mu_s' = 12.5\ \mathrm{cm}^{-1}$. The middle curve is for the less-scattering acrylic with $\mu_s' = 6\ \mathrm{cm}^{-1}$.

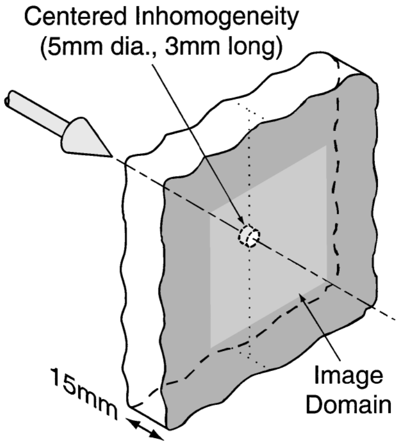

Fig. 3. Geometry of the sample used for the inhomogeneity localization experiments. The imaging domain is approximately 45 mm × 36 mm in size.

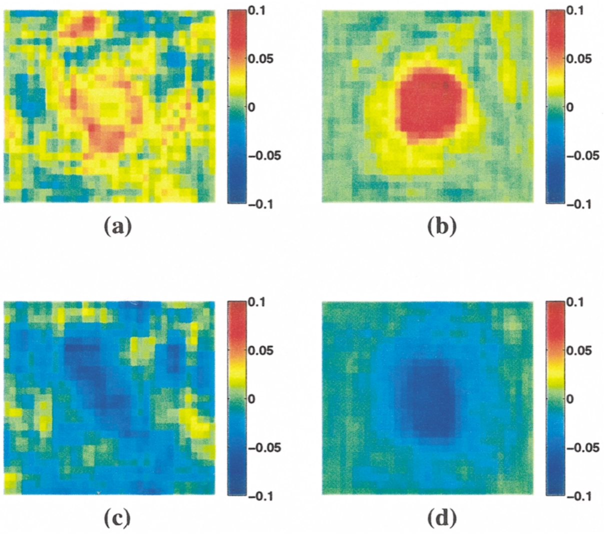

Fig. 4. Contrast-ratio difference images for each inhomogeneity at two laser linewidths: (a) void at 5 MHz, (b) void at 17 GHz, (c) heavy scatterer at 5 MHz, (d) heavy scatterer at 17 GHz. The variation in contrast ratio is shown by the color bars.

In Fig. 4(b) one can see a higher contrast ratio for the void inhomogeneity that is localized in the center of the image, which is consistent with the expectation that less scatter results in a higher contrast ratio. Conversely, in Fig. 4(d), for the heavily scattering acrylic inhomogeneity there is a lower contrast ratio localized in the center of the image, which is consistent with the expectation that more scatter results in a lower contrast ratio. These data demonstrate that we have the ability not only to identify an inhomogeneity but also to determine whether it is more or less scattering than the background.

No localization of the inhomogeneity is apparent from the contrast-ratio difference images of Figs. 4(a) and 4(c) for the 5-MHz linewidth. We can explain this result by considering Fig. 2, which shows that for such a narrow linewidth the contrast ratio is approximately unity, essentially independently of the amount of scatter in these samples. The 17-GHz linewidth in Figs. 4(b) and 4(d) is comparable with the inverse of the width of $p(L)$, for which there is much greater sensitivity of contrast ratio to linewidth and scatter variations. Our ability to synthesize the desired laser linewidth is a very important factor in localizing inhomogeneities by use of contrast-ratio difference images.

One can also attempt to form images similar to those in Fig. 4 with just the subregion mean, but these results show no sensitivity to laser linewidth. This is expected, since the mean intensity is independent of the coherence properties of the source. The relation of the laser coherence to the scattering properties of the sample, as observed through speckle contrast, is the basis for our approach to material characterization and imaging.

It is also interesting to note the parallel with photon migration imaging,[11] in which one characterizes an optically scattering sample by use of a source with a rf intensity modulation. In this approach the greatest sensitivity of the photon current (J) in modulation depth and phase to the modulation frequency is obtained when the modulation period becomes comparable with the spread in photon travel times. In our speckle approach the greatest sensitivity in contrast ratio is obtained when the laser coherence time becomes comparable with the same quantity. Thus the two approaches can provide comparable information, although the implementations are quite different. One practical advantage of our speckle contrast method is the ability to use large linewidths ($>$10 GHz) in an imaging geometry; detecting similar intensity modulation frequencies in a photon migration imaging geometry would be quite difficult.

In summary, we have demonstrated that a variable-coherence source synthesized by modulation of a tunable laser diode is important for obtaining speckle contrast data that one can employ with a diffusion equation model to characterize scattering material. This approach allows us to optimize the source coherence to enhance sensitivity to material properties and is more convenient than varying the thickness of a scattering domain. This variable-coherence speckle contrast technique can form the basis for localizing and determining the nature of inhomogeneities in optically scattering media and has applications to imaging.

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References

1. J. W. Goodman, in *Laser Speckle and Related Phenomena*, 2nd ed., J. C. Dainty, ed. (Springer-Verlag, Berlin, 1984).
2. R. A. Sprague, Appl. Opt. **11,** 2811 (1972).
3. S. L. Toh, H. M. Shang, and C. J. Tay, Opt. Lasers Eng. **29,** 217 (1998).
4. C. A. Thompson, K. J. Webb, and A. M. Weiner, Appl. Opt. **36,** 3726 (1997).
5. C. A. Thompson, K. J. Webb, and A. M. Weiner, J. Opt. Soc. Am. A **14,** 2269 (1997).
6. A. F. Fercher, M. Peukert, and E. Roth, Opt. Eng. **25,** 731 (1986).
7. H. Fujii, Med. Biol. Eng. Comput. **32,** 302 (1994).
8. P. Naulleau, D. Dilworth, E. Leith, and J. Lopez, Appl. Opt. **35,** 3065 (1996).
9. M. S. Patterson, B. Chance, and B. C. Wilson, Appl. Opt. **28,** 2331 (1989).
10. J. D. Jackson, *Classical Electrodynamics* (Wiley, New York, 1975).
11. E. M. Sevick, J. K. Friscoli, C. L. Burch, and J. R. Lakowicz, Appl. Opt. **33,** 3563 (1994).