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13. ABSTRACT (Maximum 200 words)

Our measurements of the frequency and spatial variation of the microwave field in ensembles of random samples have revealed the underlying structure of wave correlation and photon localization. The intensity correlation was found in terms of displacement and polarization shift of the source and detector can be expressed in terms of the square of the corresponding field correlation function. Nonexponential decay of pulsed transmission through disordered media was found in nominally diffusive media, in which the level width exceeds the spacing between levels. This departure from diffusion theory is interpreted in terms of the decay rate statistics of electromagnetic quasi-normal modes. The influence of these modes of the electromagnetic field is an indication of the breakdown of the particle diffusion theory. Measurements of spatial and polarization correlation as a function of time delay from an exciting pulse show that the structure of the intensity correlation function is the same as found in steady state propagation, being a function only of the corresponding field correlation functions. The degree of correlation in the speckle pattern is seen to be the key parameter in dynamics and hence in steady state propagation. We have discovered a localization laser in random one-dimensional systems.

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Table of Contents

Final Progress Report
US ARO – DAAD19-00-1-0362
6/00-12/03
A. Z. Genack
"Electromagnetic Propagation, Localization and
Lasing in Random and Periodic Media,"

During the period of this grant we have advanced the understanding of wave propagation in random and periodic systems. Highlights of our research are given below.

Photon Localization

Our measurements of the frequency and spatial variation of the microwave field in ensembles of random samples have revealed the underlying structure of wave correlation and shown the ways in which it is related to the photon localization transition.

We have carried out measurements of microwave transmission in an ensemble of random collections of alumina spheres randomly positioned in a copper tube at low density. Scattering from high index dielectric spheres is strongest when the wavelength is comparable or smaller than the diameter of the spheres. Strong scattering near the first five Mie resonances is evident from the observation of precipitous drops in transmission and sharp peaks in photon transit time, seen in Figs. 1a and 1b, respectively [71-1]. However, waves are localized only in a narrow frequency window above the first resonance, as indicated by the rise of relative fluctuations above the critical value of 7/3 at the threshold of the localization transition (Fig. 1c) [71-1,A]. Within this window, the probability distribution for intensity becomes extraordinarily broad [73-2]. At the same time, in contrast to the behavior for diffusing waves, the photon transit time becomes correlated with the transmitted intensity (Fig. 1d) [73-2]. This is consistent with the expectation that for localized waves the transmitted intensity and photon dwell time are each high when the wave is at resonance with a

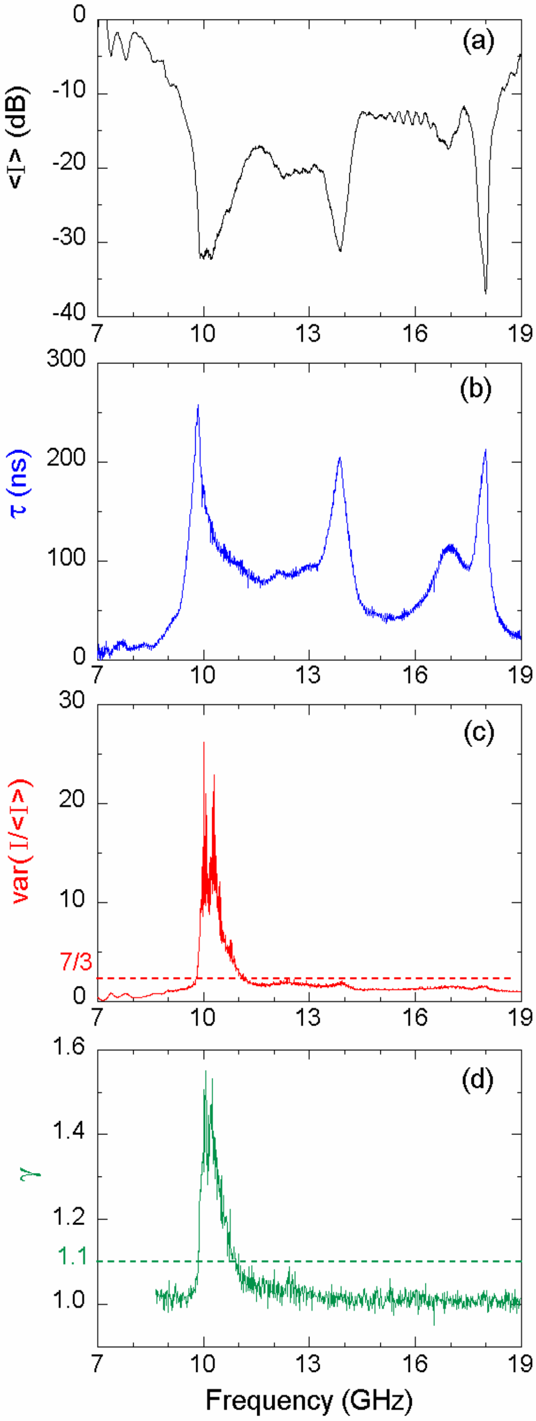

Figure 1. (a) Average transmitted intensity, <I>, (b) average photon transit time, $\tau = \langle I\varphi'\rangle/\langle I\rangle$, φ' is the spectral derivative of the phase accumulated by the field as it propagates through the sample, (c) variance of normalized transmitted intensity, var(I/<I>), and (d) dimensionless ratio, $\gamma = \langle I\varphi'\rangle/\langle I\rangle\langle\varphi'\rangle$, versus frequency in a quasi-1D alumina sample of L=80 cm and alumina volume filling fraction f=0.068. The dashed lines indicate the

localized state. Localization occurs when this correlator is greater than 1.1.

When the sample is thinner than the absorption length, we find that the ratio of the field correlation frequency and the mode spacing, known as the Thouless number, gives a reliable measure of the extent of localization, which is consistent with measurements of relative intensity fluctuations [71-1]. The minimum of the Thouless number occurs above the first Mie resonance as a result of a sharp drop in the density of states due to collective scattering. These results allow us to chart the changing character of static and dynamic wave statistics through the Anderson localization transition.

Spatial and polarization correlation of vector waves

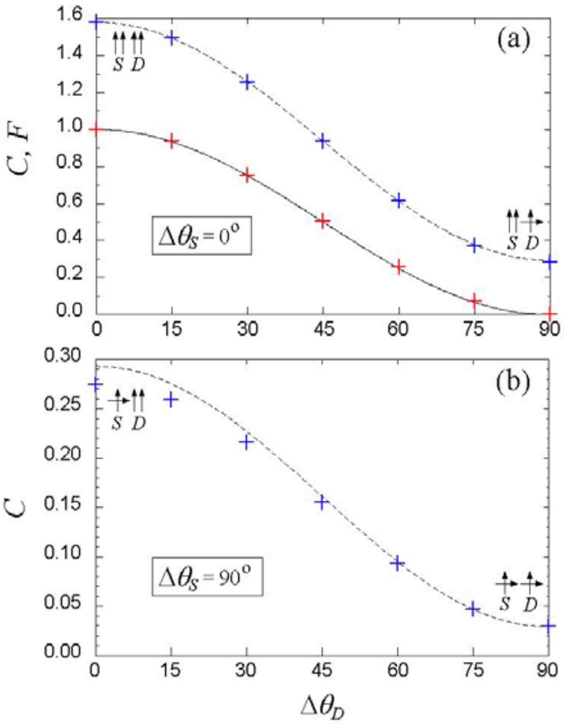

Figure 2. (a) Intensity correlation functions C and square of field correlation function F plotted versus $\Delta\theta_D$ for $\Delta\theta_S = 0$. The solid line is the prediction, $F(\Delta\theta_D) = \cos^2(\Delta\theta_D)$. The dashed line is the fit of $C(0,\Delta\theta_D)$ to the first 4 data points. (b) C versus $\Delta\theta_D$ for $\Delta\theta_S = 90^0$. The dashed line is the prediction $A_3 + A_2 \cos^2\Delta\theta_D$ with the A_2 and A_3 found from the fit in (a).

Our measurements of microwave radiation transmitted through randomly positioned Polystyrene spheres showed that spatial correlation of transmitted intensity may be expressed in terms of the square of the field correlation function of the field as a function of displacement of the source and the detector [72-3]. This explicitly showed the way in which long-range correlation, the essence of mesoscopic physics, emerges from correlations in the randomly fluctuating field. In this work, the leading term obtained by factorizing the field, as well as the term associated with long-range intensity correlation, were observed. A diagrammatic calculation of the correlation function up to second order in the expansion parameter $1/g$, where g is the dimensionless conductance, was carried by Pnini and Shapiro in order to understand the microwave measurements. The results of the calculations were in agreement with observations when terms of order 1 and $1/g$ were included and also suggested the structure of a term of order $1/g^2$. This last term was buried in the noise of our measurements. To study samples in which this term was larger, we studied samples of alumina spheres for which the value of g was smaller. Rather than study spatial correlation in these samples, we studied field and intensity correlation with shift of the polarization of the incident and transmitted wave. Studies of polarization correlation have allowed us to focus specifically on the vector character of electromagnetic waves, which for the most part had been suppressed in studies of wave statistics. We conjectured that the correlation function of intensity with polarization should have the same dependence upon the field correlation function as is the case with the intensity correlation function with position. The separation of contributions to the correlation function is particularly straightforward, however, in the case of polarization because the field correlation is of a particularly simple form which is independent of the value of g. It is simply the cosine of the shift in the angle of polarization of either the source or the detector. This has allowed us to separate out the short, long and infinite-range contributions to the correlation function. [4] Studies of the frequency dependence each of these terms has allowed us to break up each of these contributions into a universal component, with a magnitude that depends upon g, and a nonuniversal component that depends upon details of the scattering medium at the input or output of the sample. This component involves a short short-lived interaction with the input or output surface and hence a large correlation frequency. Thus the residual correlation at large frequency shift can be ascribed to nonuniversal interactions. [4] This is illustrated in Fig. 2.

Statistics of transverse flux in random media

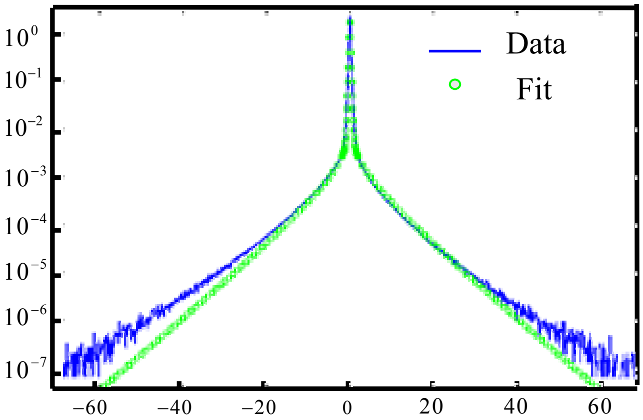

Figure 3. Comparison of measurements of probability distribution P(Idφ/dx) and Gaussian theory. The exponential decrease near the peak gives the ratio of the phase and transport velocities.

Interference between multiply scattered waves reaching a point in a random medium leads to large field fluctuation in the transmitted speckle pattern. We measure the probability distributions of dφ/dx, as well as of Idφ/dx for transmitted microwave radiation, where φ is the phase accumulated by a field as it traverses the sample, x is the transverse position on the output surface, and I is the transmitted intensity. This probability distribution is shown in Fig. 3. The transverse photon flux is given by Idφ/dx. We find that long-range correlation affects the statistics of Idφ/dx but not of dφ/dx. We find that the probability distribution of Idφ/dx depends upon the ratio of the phase and transport velocity. This is rather surprising since the statistics of this quantity can be determined by measurements at a single frequency and might have been expected to reflect static behavior exclusively. The precise dependence upon the transport velocity and its variation as the detector is moved from the near field to the far field is under investigation.

Breakdown of diffusion in dynamics of extended waves

We have found nonexponential decay of pulsed transmission through disordered media in nominally diffusive media, in which the level width exceeds the spacing between levels, even at long times and in thick samples [5]. This departure from diffusion theory is interpreted in terms of the decay rate statistics of electromagnetic quasinormal modes. The influence of these modes of the electromagnetic field is an indication of the breakdown of the particle diffusion theory. The statistics of these modes is fundamental to understanding the static and dynamic behavior of waves in both passive and active random media. The decay of the pulse in various samples composes of random mixtures of low-density alumina spheres are shown in Fig. 4a. Diffusion theory predicts a constant decay rate at long times associated with the decay of the lowest diffusion mode. Instead, we find, as shown in Fig. 4b, that the decay rate falls at a nearly constant rate. This is associated with the width of the distributions of decay rates of the underlying electromagnetic modes in the medium. A linear fall of the decay rate has been predicted by Mirlin, [6] but the scaling is rather different than found in our measurements. We have recently measured the decay of transmission of localized modes. We find that the decay is indicative of a lognormal distribution of decay rates.

In collaboration with Z.Q. Zhang we have solved the Bethe-Salpeter equation including recurrent scattering in a self-consistent manner to find nonexponential decay within a random quasi-one dimensional sample [7]. The discrepancies with the calculations by Mirlin [6] are explained. In the limit of a slab geometry the decay rate saturates to a constant renormalized value, which depends upon sample thickness.

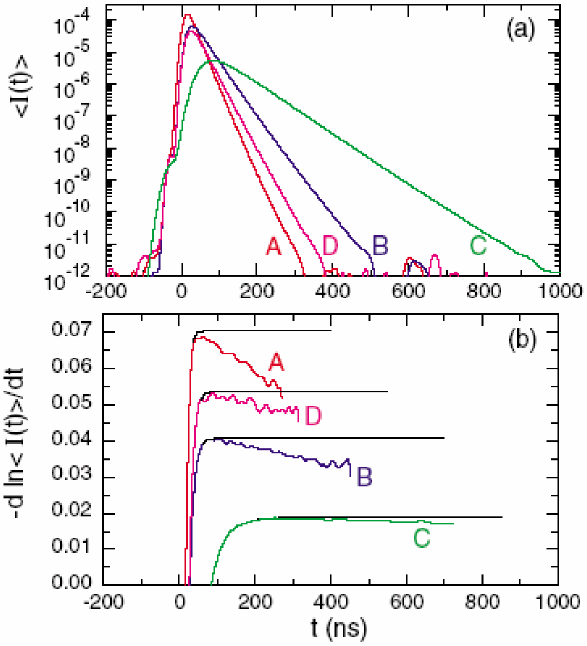

Figure 4. (color online). (a) Average transmitted intensity in samples *A–D*. (b) Temporal derivative of the logarithm of the intensity gives the rate of the intensity decay due to leakage out of the sample and absorption. The thin black curves are the decay rates of the diffusion model.

Transmission through chiral twist defects in anisotropic periodic structures

We have observed a long-lived photonic state in measurements of microwave transmission through a helical stack of anisotropic overhead transparencies with various twist defects in the center of the structure. [8] Once account is taken of absorption and of the angular spread of the source, computer simulations of transmission through a polarized localized state [9] are in agreement with measurements. Unlike for isotropic one-dimensional band gaps, the intensity of the localized mode is not modulated in space on a wavelength scale. This work has enhanced our understanding of resonances in chiral media and stimulated our recent implementation of the chiral structure into a fiber geometry. [B]

Chiral fibers

We demonstrated a polarization-selective photonic stop band in a new chiral fiber structure with double-helix symmetry [B]. The stop band exists for only circularly polarized radiation with the same handedness as the structure and is centered at a wavelength in the fiber equal to the fiber pitch. When one part of the chiral fiber is twisted about its axis, a localized mode is produced, which can be tuned across the gap by changing the twist angle. Observations in single-mode fibers are in good agreement with one-dimensional simulations of a dispersive cholesteric material. At higher frequencies, however, we find a sharp onset of a broad polarization selective scattering band, which is not present in one-dimensional simulations. These fibers have applications as broad and narrowband filters and polarizers and as fiber lasers.

Time dependent statistics

We have begun to analyze spectral and spatial measurements of microwave transmission to obtain the degree of correlation and intensity distributions as a function of time delay. Andrey Chabanov and Bing Hu have found in analyses of measurements on different samples that the degree of intensity correlation and the variance of the intensity increase with time [10]. Analysis of transmission data for different polarization of source and detector indicate that it is possible to obtain separately the time dependence of the degree of short, long and infinite-range correlation. It is also possible to observe the influence of gain upon transmission in these microwave measurements. Gain can be added by Fourier transforming spectra to give the time dependence of the filed and then multiplying the field versus time by an exponentially increasing factor. The statistics of the field for an amplifying medium can thereby be studied. We believe this approach will give detailed statistical information that addresses core issues related to lasing in random media. For example, it will be of particular interest to explore the dynamics of samples in which the effective "time-dependent diffusion coefficient" was found to decrease with time. We expect that the spectra associated with such sample will show substantial narrowing of peaks and it may be possible to observe particular long-lived modes in these systems. Lasing would be initiated in such long-lived modes in amplifying optical samples.

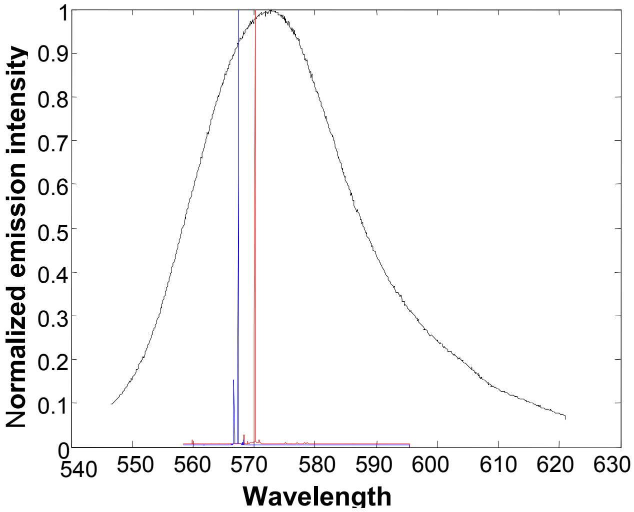

Figure 5. Spectrum of the two localized lasing modes (red and blue lines) at two different location in the sample. Black line shows the spectrum of spontaneous emission from the gain medium.

Localization Laser

We have recently obtained the results shown in Fig. 5. for a 25 μm thick layer of a dilute solution of Rhodamine 6G dye in ethylene glycol in the center of the sample. Similar results are obtained if the dye solution is placed throughout the sample with two glass slide layers between each dye layer. As a result of the

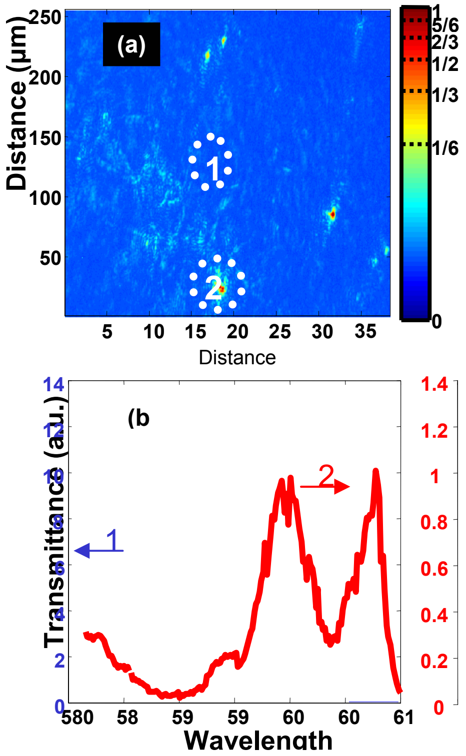

Figure 3. (a) Spatial map of transmittance of CLC sample at 605 nm. (b) Spectra of transmittance at two different locations: blue curve corresponds to location "1" on the map, and red curve – to location "2".

1D geometry, both the pump and emitted waves are localized. Thus it is possible for the peak intensity for both the pump and the emission modes to occur deep within the sample. Neither absorption nor amplification in the sample would substantially affect the spatial distribution of energy in the mode or its frequency [5, 11-14] so that the modes excited are characteristic of those in the 1D random medium. The lowest threshold is achieved when the peaks of both these localized modes overlap at the center of the sample. This produces facile lasing at a few distinct frequencies.

Lasing in polymeric liquid crystals

In perfectly periodic anisotropic chiral layered materials, such as CLCs, lasing occurs at the edge of the photonic stop band.[15] In the presence of disorder in polymeric CLCs, however, we find lasing within the stop band. This may be due to long-lived localized modes within the stop band created by disorder. The nature of propagation will be determined from spatial and spectral maps of the transmitted beam. The nature of propagation in areas from which lasing occurs within the photonic stop band will be of particular interest. An example of a spatial probe of transmission using an expanded plane wave and transmission spectra at two points in the sample is shown in Fig. 6.

Listing of publications supported under this grant

(a) Papers published in peer-reviewed journals

"Large coherence area thin-film photonic stop-band lasers," V.I. Kopp, Z.-Q. Zhang and A.Z. Genack, Phys. Rev. Lett. **86**, 1753 (2001).

"Photon Localization in Resonant Media," A.A. Chabanov and A.Z. Genack, Phys. Rev. Lett. **87**, 153901 (2001).

"Lasing from a stiff chain polymeric lyotropic cholesteric liquid crystal," P.V. Shibaev, K. Tang A. Genack, V.I. Kopp, M. M. Green, Macromolecules **35**, 3022 (2002).

"Spatial field correlation: the building block of mesoscopic fluctuations," P. Sebbah, B. Hu, A.Z. Genack, R. Pnini and B. Shapiro, Phys. Rev. Lett. **88**, 123901 (2002).

"Twist defect in chiral photonic structures," V.I. Kopp and A.Z. Genack, Phys. Rev. Lett. **88**, 033901 (2002).

"Photon localization in resonant media," A.A. Chabanov and A.Z. Genack, Optics and Photonics News, 13, 25 (2002).

"Transmission through chiral twist defect in anisotropic periodic structures," V.I. Kopp, R. Bose and A.Z. Genack, Opt. Lett. 28, 349 (2003).

"Lasing in chiral photonic structures," V.I. Kopp, Z.-Q. Zhang and A.Z. Genack, Prog. in Quant. Elec. **27**, 369-416 (2003).

"Breakdown of diffusion in dynamics of extended waves in mesoscopic media," A.A. Chabanov, A.Z. Genack and Z.-Q. Zhang, Phys. Rev. Lett. **90**, 203903 (2003).

"Double helix chiral fibers," V.I. Kopp and A.Z. Genack, Opt. Lett. **28**, 1876 (2003).

"Photonic Materials Based on Mixtures of Cholesteric Liquid Crystals with Polymers," P.V. Shibaev, V.I. Kopp and A.Z. Genack, to be published in Jour. Phys. Chem. B, **107** 6961 (2003).

"Narrowing of spontaneous emission and lasing in lyotropic and thermotropic liquid crystals," P.V. Shibaev and A.Z. Genack, Liq. Cryst. **30**, 1365-1368 (2003).

"Lasing from chiral photonic band gap materials based on cholesteric glasses," P.V. Shibaev, V.I. Kopp, A.Z. Genack, and E. Hanelt, Liq. Cryst. **30**, 1391-1400 (2003).

(b) Papers published in non-peer-reviewed journals or in conference proceedings

"Anisotropic photonic band gap structures," V.I. Kopp. P.V. Shibaev. R. Bose, and A.Z. Genack, Proc. SPIE, **4655**, 141 (2002).
"Mesoscopic dynamics: a study of phase," A.Z. Genack, A.A. Chabanov, P. Sebbah and B.A. van Tiggelen in *Wave Scattering in Complex Media,* ed by and B.A. van Tiggelen and S.E Skipetrov (Kluwer, Dordrecht, 2003).
"Photon localization in resonant media," A.A. Chabanov and A.Z. Genack in *Wave Scattering in Complex Media,* ed. by and B.A. van Tiggelen and S.E Skipetrov (Kluwer, Dordrecht, 2003).

(c) Papers presented at meetings, but not published in conference proceedings

"Correlation in polarization of electromagnetic waves in random media," A. A. Chabanov, A. Z. Genack, N. Tregoures and B. A. van Tiggelen, PIERS 2000 (Cambridge, MA, July 2000).
"Photon localization and lasing," A.Z. Genack and A.A. Chabanov, Conference on Wave Propagation in Diffusive and Nonlinear Media (Cargese, France, September 2000).
"Statistics of dynamics of localized waves in random media," A.Z. Genack and A.A. Chabanov, Conference on Wave Propagation in Diffusive and Nonlinear Media (Cargese, France, September 2000).
"Correlation in polarization of EM wave in random media," A.A. Chabanov, A.Z. Genack, N. Tregoures, and B. A. van Tiggelen," A. Chabanov and A.Z. Genack, March APS Meeting (Seattle, March 2001).

"Photon localization in resonant media," A. Z. Genack and A.A. Chabanov, (I) OSA Annual Meeting (Long Beach, CA, October 2001).

"Anisotropic Photonic Band Gap Structures," V.I. Kopp, P.V. Shibaev, R. Bose, and A.Z. Genack, SPIE Photonics West, Optoelectronics 2002 (San Jose, January 2002)
"Photon localization in resonant media," A. Z. Genack, (I) APS March Meeting (Indianapolis, Indiana, March 2002).
"Structure of Spatial Intensity Correlation for Diffusing Waves through Quasi-1D Random Medium," B. Hu, A.Z. Genack, P. Sebbah, R. Pnini and B. Shapiro, APS March Meeting (Indianapolis, Indiana, March 2002).
"Statistics of static transmission for diffusing and localized waves," A.A. Chabanov and A.Z. Genack, APS March Meeting (Indianapolis, Indiana, March 2002).
"Twist Defect in Chiral Photonic Structures," V.I. Kopp and A.Z. Genack, NATO Advanced Study Institute, Wave Scattering in Complex Media, From Theory to Applications, (Cargese, France, June 17 2002).
"Spatial Field and Intensity Correlation of Diffusing Waves," B. Hu, A.Z. Genack, P. Sebbah, R. Pnini, and B. Shapiro, OSA Annual Meeting, Orlando (October, 2002).
"Photonic Band Gaps in Chiral Structures," A.Z. Genack, OSA Annual Meeting, Orlando (October, 2002).
"Electromagnetic Propagation and Localization in Quasi-1D Random Media," A.A. Chabanov and A.Z. Genack, OSA Annual Meeting, Orlando (October, 2002).
"Photon Localization and Correlation," Conference on Multiple Scattering and Partial Coherence, Costa Mesa, (January, 2003).

"Statistics of Transverse Flux in Random Media ," B. Hu, A.Z. Genack, P. Sebbah and B.A. van Tiggelen, OSA Annual Meeting, Frontiers in Optics, Tucson (October, 2003).
"Mesoscopic Correlation in Electromagnetic Wave Polarization," A.Z. Genack, A.A. Chabanov, N. Tregoures, and B.A. van Tiggelen, OSA Annual Meeting, Frontiers in Optics, Tucson (October, 2003).
"Lasing in Chiral Microlasers," (I) A.Z. Genack, V. Milner, V.I. Kopp, P.V. Shibaev, and J. Singer, OSA Annual Meeting, Laser Science XIX, Tucson (October, 2003).
"Absence of Diffusion in Wave Dynamics," Z.Q. Zhang, S.K. Cheung, X. Zhang, A.A. Chabanov, and A.Z. Genack, OSA Annual Meeting, Frontiers in Optics, Tucson (October, 2003).

In addition to these papers many colloquia and seminars have been given relating to this work including:

"Statistical approach to photon localization," phase and dynamics of microwaves in random media," A.Z. Genack and A.A. Chabanov, PIERS 2000 (Cambridge, July 2000).
"Statistical approach to photon localization," A.Z. Genack, Army Research Laboratory (Aberdeen Proving Grounds, MD, September 2000)
"Photon localization in resonant media," A. Z. Genack, Department of Physics, City College of CUNY (March 2001).
"Photon localization in resonant media," A. Z. Genack, Department of Physics, Northwestern University (May 2001).
"Optical Propagation and Lasing in Cholesteric Liquid Crystals," Polytechnic University of New York, (April 10, 2002)
"Statistics of Photon Localization in Resonant Media," University of Twente, the Netherlands (April 15, 2002).
"Photon Localization in Resonant Media," A.Z. Genack, Hunter College of CUNY (November, 2002).
"Photonics of Chiral Media," City College of CUNY (December, 2002).
"Photonics of Chiral Media," University of Nice-Antipolis/CNRS (July 10, 2003).
"Photonics of Chiral Structures," A.Z. Genack, University of Utah, Salt Lake City (November, 2003).

(d) Manuscripts submitted but not published

"Polarization correlation in random media," A.A. Chabanov, A.Z. Genack, N. Tregoures and B.A. van Tiggelen, submitted to Phys. Rev. Lett., cond-mat/0309114 (2003).
"Impact of weak localization in the time domain," S.K. Cheung, X. Zhang, Z.Q. Zhang, A.A. Chabanov, A.Z. Genack, submitted to Phys. Rev. Lett., cond-mat/0311184 (2003).

(e) Technical reports submitted to ARO

"Photonics of Chiral Media," University of Nice-Antipolis/CNRS (July 10, 2003).

Participating scientific personnel

Two graduate students were involved in this research. Andrey A. Chabanov received his degree in June, 2001, and Bing Hu is slated to receive her degree in June 2004. Bing Hu has carried out microwave measurements of field and intensity correlation in random waveguides, which have allowed her to find steady state and time dependent correlation function in space. She has also measured the statistics of waves in one-dimensional waveguides, and mapped out the field on the output area of a random sample. Andrey Chabanov served briefly as a postdoctoral fellow after receiving his degree and carried out microwave steady state measurements of photon localization from which the time dependence of statistics were obtained. Andrey next carried out research at the Department of Chemical Engineering at the University of Minnesota. Since last October, Valery Milner has served as a postdoctoral fellow. He is studying lasing in polymeric liquid crystals and has developed the localization laser based on one-dimensional localization. In addition, Jerome Klosner, a retired professor of mechanical engineering, has worked on the problem of localization in single-mode waveguides. Two undergraduates Gabi Krauss and Larry Corrales have worked on microwave localization in 1D waveguides and random lasing, respectively.

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