

Random distributed feedback fibre laser

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The concept of random lasers making use of multiple scattering in amplifying disordered media to generate coherent light has attracted a great deal of attention in recent years. Here, we demonstrate a fibre laser with a mirrorless open cavity that operates via Rayleigh scattering, amplified through the Raman effect. The fibre waveguide geometry provides transverse confinement and effectively one-dimensional random distributed feedback, leading to the generation of a stationary near-Gaussian beam with a narrow spectrum, and with efficiency and performance comparable to regular lasers. Rayleigh scattering due to inhomogeneities within the glass structure of the fibre is extremely weak, making the operation and properties of the proposed random distributed feedback lasers profoundly different from those of both traditional random lasers and conventional fibre lasers.

The physical effects accompanying light propagation in random media are important for practical engineering applications such as laser radars, biomedical imaging, remote sensing, communications, ranging and distance measuring and optical astronomy. However, problems in wave transport and the interactions of light with random media also present exciting and formidable challenges to modern science. Recent developments in photonics have shown that it is possible to make practical use of the intrinsic or artificial disorder in materials, leading to new types of optical elements and systems. In particular, the propagation of light in amplifying disordered media, such as powders consisting of laser crystal particles, has attracted a great deal of attention both as a fundamental physical problem at the interface of laser physics, quantum optics and the mathematical theory of disordered systems, and as an optical engineering approach that has allowed demonstrations of new, interesting devices such as random lasers (for a review see refs 1–3). A basic laser scheme normally requires two key elements: a gain material that provides amplification and an optical cavity that traps the light, creating a positive feedback. Lasing occurs when the total gain in the cavity overcomes the total cavity loss. Operational characteristics of conventional lasers are determined both by the distinctive features of the gain medium and by the cavity design that defines the structure of laser modes. However, in random lasers with no cavity (or with an open cavity), the multiple scattering of photons in an amplifying disordered medium increases the effective optical path, resulting in lasing that was theoretically predicted in ref. 4 and experimentally demonstrated in refs 5–7. The output characteristics of random lasers are determined by the build-up of the radiation by multiple scattering in the gain medium, resulting in randomly embedded local spatial modes that may coexist with non-localized extended modes^{8,9}.

Random lasers have clear advantages, including simple technology (no need to form a precise microcavity) and low production costs. However, for many applications, their current performance has to be modified for them to be able to challenge conventional lasers. Significant recent progress in the theoretical understanding and experimental advances in random lasers shows that this is feasible (see, for example, refs 9–12). At the same time, the special properties of random lasers, such as pulsed operation with complex

features in emission spectra and angular dependence, can be retained³. Various schemes can be applied to improve the performance of random lasers with the challenging goal of achieving stationary operation with beam quality comparable to those of conventional lasers. For instance, it has been shown in ref. 13 that less complex lower-dimensional systems such as random multilayers with disorder may provide directional output.

Here, we demonstrate a new type of one-dimensional laser with random distributed feedback based on Rayleigh scattering (RS)¹⁴, which is naturally present in any transparent, continuous glass medium. The cylindrical fibre waveguide geometry provides transverse confinement, although the cavity is open in the longitudinal direction and does not include any regular reflectors. Although RS in the fibre core is extremely weak, the effect may be accumulated over a long distance. Using stimulated Raman scattering to provide distributed amplification we demonstrate stationary lasing in low-cost, open-cavity, standard transmission fibre with random distributed feedback.

Results

The proposed principle of laser operation is illustrated in Fig. 1. The laser medium is a conventional optical fibre (of total length $L = 83$ km in this experiment) with a loss coefficient $\alpha \approx 0.045$ km⁻¹ (0.2 dB km⁻¹) in the $\sim 1,550$ nm transparency window of silica glasses¹⁵. In this wavelength region, the attenuation is mainly determined by RS. The backscattering coefficient (the part of the scattered radiation that is scattered back into the core of the fibre waveguide per unit length) is as small as $\epsilon = 4.5 \times 10^{-5}$ km⁻¹. Therefore, the total backward radiation within the fibre is negligibly small (<0.1%) even in a ~ 100 -km-long passive fibre. However, the situation is dramatically changed when the scattered radiation is amplified. In this experiment, amplification was implemented by coupling two equal-power 1,455 nm pumping waves into the centre of the fibre in opposite directions, thus providing distributed Raman gain with the coefficient $g_R \approx 0.39$ km⁻¹W⁻¹ at $\sim 1,550$ nm, shifted relative to the pump wavelength in accordance with the typical Stokes shift of ~ 13 THz (ref. 16).

The Raman gain for the $\sim 1,550$ nm wave exceeds losses up to a distance $|z| = L_{RS}$ in both directions. The interval $2L_{RS}$ corresponds to the amplification region of the fibre in which the generated

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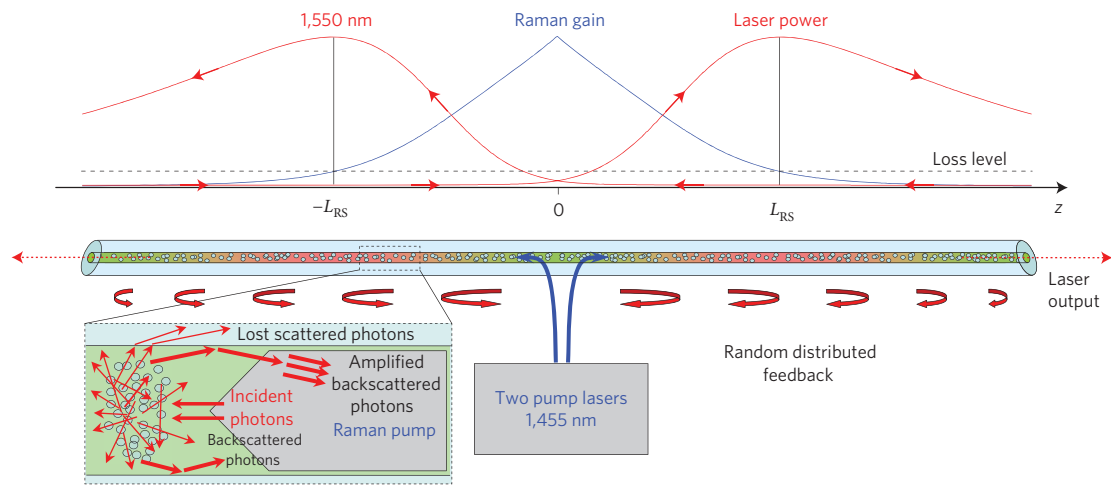


Figure 1 | Principle of random distributed feedback fibre laser operation. Photons propagating in a long fibre are coherently scattered by random refractive index inhomogeneities complying with Rayleigh's law. Most of the scattered photons leak out of the fibre core. Only $Q \approx 1 \times 10^{-3}$ of them are backscattered and guided by the fibre. Two pump waves coupled at $z = 0$ provide distributed Raman gain along the fibre. The backscattered guided photons can be amplified if total gain (blue) is larger than the loss level (dashed line), which is true for all points $|z| < L_{RS}$. As a result, forward (red line, right arrows) and backward (red line, left arrows) propagating waves are generated. The numerically calculated laser power distribution and Raman gain are shown.

radiation, as well as the backscattered radiation, are amplified. At $|z| > L_{RS}$, the generated power is attenuated before leaving the fibre. Angled cleaves were used at the fibre end facets to eliminate reflections and ensure that the feedback was due only to the randomly distributed scattering.

Figure 2 clearly demonstrates lasing with a threshold pump power of ~ 1.6 W and a typical linear growth of the generated output power above threshold. An output power as high as 150 mW was observed from each (left and right) fibre end, limited mainly by the available pump lasers. The total output power is double that of the single side power, resulting in a slope efficiency of up to 30%.

Near threshold, lasing starts from the generation of stochastic pulses (Fig. 3) with amplitudes much higher than the quasi-stationary background. The corresponding optical spectrum shown in Fig. 4a shows the typical broadband shape of the Raman gain curve of the amplified spontaneous emission (ASE) superimposed with the random spikes and dips in the tails characteristic of stochastic pulse generation with gain saturation. Measurements of the radio-frequency beating spectrum show the presence of a narrow peak at ~ 11 GHz corresponding to the Stokes shift of the stimulated Brillouin scattering (SBS) process, similar to the radio-frequency spectra of self-Q-switched fibre lasers with combined RS-SBS feedback^{17,18}. Note that the effect of distributed RS feedback was first observed in a Brillouin laser¹⁹, resulting in significant reduction of the laser linewidth. However, its output power remained nearly the same and unstable, as for the SBS without RS feedback, because of very high SBS gain resulting in almost full pump depletion at a single pass. Because the SBS has a relatively low threshold and narrow bandwidth, the increase of pumping power in the presence of the RS feedback leads to generation of higher-order SBS Stokes waves and instability of the continuous wave (c.w.) regime that might lead to self-Q-switch regimes²⁰.

In our experiment, the situation completely changes when the pump power is increased well above the threshold value. At a pump power of > 2 W, the laser begins to operate in the c.w. regime with strongly suppressed amplitude fluctuations (Fig. 3). The optical spectrum is also stabilized (Fig. 4b), showing two narrow (full-width at half-maximum, FWHM < 1.5 nm) laser lines localized near the Raman gain maxima. In the radio-frequency spectrum, neither the Brillouin scattering peak at ~ 11 GHz nor the mode beatings with spacing $c/2Ln$ corresponding to the roundtrip in the cavity with length $L = 83$ km are seen, in contrast to the

situation in a conventional fibre Raman laser of nearly the same length, in which the cavity is formed by two gratings: for a conventional fibre Raman laser, a clear mode structure with mode spacing $c/2Ln \approx 1.2$ kHz is observed²¹. For the random laser, the generated optical spectra are ~ 35 dB above the noise level and are orders of magnitude narrower than the ASE spectrum (see inset in Fig. 4b). In the transverse direction, the generated radiation has the form of the fundamental mode of the fibre waveguide, providing a near-Gaussian profile of the output beam. Thus, in spite of purely random weak distributed feedback, stationary laser operation is clearly demonstrated.

The fibre length required for lasing based on the random distributed RS feedback can be estimated as follows. Neglecting pump depletion due to Stokes wave generation, the longitudinal distribution of the Raman gain $g_R P_p(z)$ is defined by the pump power attenuation $P_p(z) = P_0 \exp[-\alpha_p |z|]$, where $\alpha_p \approx 0.057 \text{ km}^{-1}$. The length of the amplification region estimated through the gain/loss balance condition, $g_R P_p(L_{RS}) = \alpha$, gives $L_{RS} = \ln(g_R P_0 / \alpha) / \alpha_p \approx 35$ km at threshold, with total input pump power $2P_0 = 1.6$ W. Thus, the

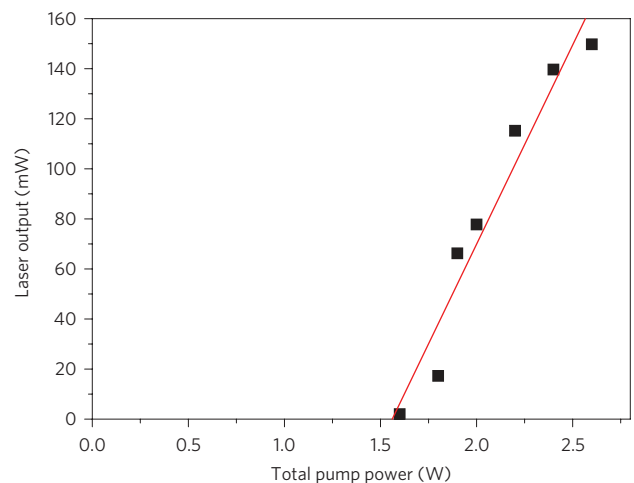


Figure 2 | Random DFB fibre laser power from the right output fibre end as a function of the total input pump power. The pump wavelength is 1,455 nm and the laser wavelengths are 1,557 and 1,567 nm. The slope efficiency (single side output) is 15%.

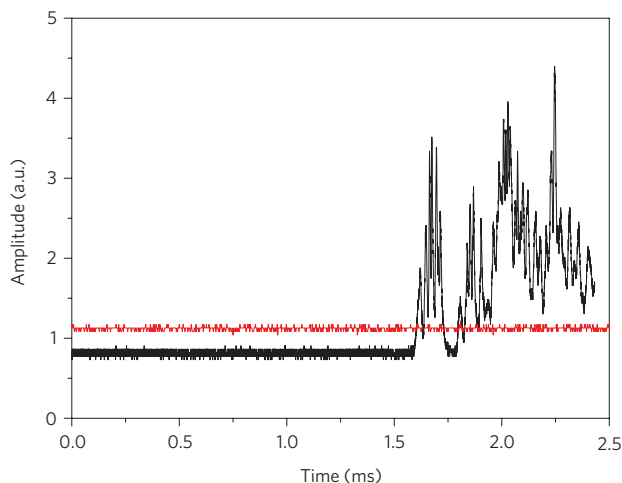


Figure 3 | Random DFB fibre laser dynamics near (black curve, input pump power $2P_0 = 1.9$ W) and well above (red curve, pump power $2P_0 = 2.4$ W) the generation threshold.

fibre length used in the experiment, $L \approx 2L_{RS}$, enables lasing due to random distributed feedback (DFB). A further increase of fibre length to $L \gg 2L_{RS}$ has little impact on lasing. In particular, the generation threshold will be only slightly reduced because of attenuation of the backscattered light in the region $|z| > L_{RS}$. At the same time, the attenuation of the generated wave in this region leads to exponential decay of the output power.

A more detailed theoretical description is based on the equation for the generated power evolution, accounting for average Rayleigh backscattering with coefficient ε :

$$\frac{dP^\pm}{dz} = \mp \alpha P^\pm \pm g_R(P_p^+ + P_p^-)P^\pm \pm \varepsilon P^\mp \quad (1)$$

where $P^\pm(z)$ are the generated Stokes waves and $P_p^\pm(z)$ are the pumping waves, with \pm corresponding to forward and backward propagation, respectively. In our numerical simulations, however, we used a more accurate full model that includes attenuation, spontaneous emission, power depletion and backscattering for both pumping and generated waves. The corresponding power distributions of the generated Stokes waves for the experimental conditions considered here are shown in Fig. 1, together with the pump-induced Raman gain distribution.

The threshold condition is defined by the integral gain/loss balance equation at the ‘roundtrip’ within a fibre with the effective ‘distributed mirror’, formed by the Rayleigh backscattering: $\varepsilon \int_0^{L/2} dz \exp[-2\alpha z + 2g_R \int_0^z P_p(s) ds] = 1$. Using a standard saddle-point approximation, one can derive from here an analytic expression for the threshold in the long-length limit $L \gg 2L_{RS}$:

$$P_0 = \frac{\alpha}{g_R} \left(1 + \ln \left(\frac{g_R P_{th}}{\alpha} \right) \right) + \frac{\alpha_p}{2g_R} \ln \left(\frac{1}{\varepsilon} \sqrt{\frac{\alpha \alpha_p}{\pi}} \right) \approx 0.8 \text{ W} \quad (2)$$

for each arm, which agrees with the observed experimental threshold of 1.6 W. The dependence of threshold pump power for lasing with RS feedback, $P_{th}^{RS} = 2P_0$, on the fibre length has also been calculated numerically using the full model (see Fig. 5). For the random RS feedback, the calculated threshold tends to a constant value for long lengths and increases abruptly at $L < 2L_{RC} \approx 70$ km, in full agreement with the theoretical estimate.

For comparison, calculations have also been performed for the lasing threshold in a conventional fibre Bragg grating (FBG) cavity formed by two highly reflecting FBGs localized at the ends

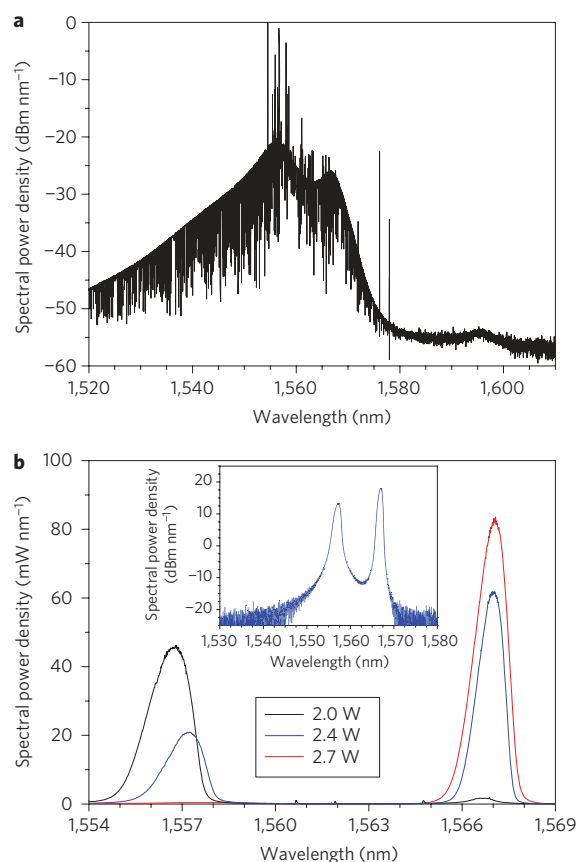


Figure 4 | Random DFB fibre laser spectra. **a**, Laser spectrum near the lasing threshold in the non-stationary regime. The Raman gain profile is saturated over a broad range and stochastic pulses are generated at random frequencies. **b**, Laser spectra in the c.w. regime at different total input pump power levels. Insert: log-scale output spectrum at 2.4 W pumping. ASE suppression is ~ 35 dB.

of the fibre span²². For the conventional FBG cavity, neglecting the effect of Rayleigh scattering, the threshold condition is given by $\exp[-2\alpha L + 2g_R \int_0^{L/2} P_p(z) dz] = 1$. The threshold power for an FBG cavity, P_{th}^{FBG} , grows linearly with its length L , and at some point may exceed the threshold for RS-based lasing. Thus, at a certain cavity length, the Rayleigh scattering becomes critically important, even in standard laser schemes with FBG-based reflectors. Corresponding numerical simulations with the RS term included are shown in Fig. 5. For a cavity longer than some critical length ($L_{cr} \approx 300$ km for the studied system), the presence of FBGs does not have any impact on the lasing threshold, as this is fully determined by the Rayleigh backscattering, $P_{th}^{FBG} \approx P_{th}^{RS}$. This means, in particular, that fibre lasers with conventional cavities made of highly reflecting mirrors/gratings with a cavity mode structure have a principal limitation in length of $L_{cr} \approx 300$ km.

The random inhomogeneities of the refractive index in the fibre core are ‘frozen’—they present a fingerprint of a particular fibre span defined by material and fabrication imperfections. Therefore, the partial reflections are random in space, but fully deterministic in time (both for amplitude and phase), interfering coherently with each other. Any random spatial sequence of distributed reflectors in terms of the Fourier presentation can be thought of as a sum of a large number of very weak regular gratings with fixed periods. A single periodic grating inscribed in an amplifying fibre is nothing more than a conventional DFB laser generating a single longitudinal mode²³. In this sense the random DFB laser based on RS may be thought of as the sum of a multitude of monochromatic DFB

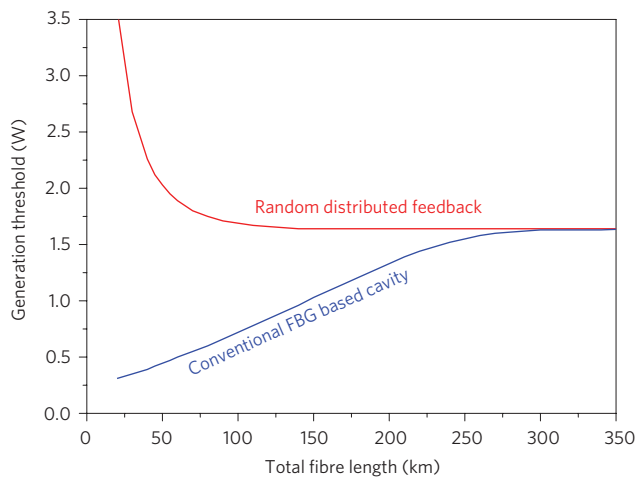


Figure 5 | Random DFB fibre laser generation threshold. The threshold pump power as a function of fibre length is numerically calculated for two cases: pure random distributed feedback and a conventional FBG-based cavity assisted by Rayleigh scattering.

lasers with arbitrary phase and amplitude, which sum into the resulting multifrequency output. Conventional DFB fibre lasers make use of a strongly reflecting grating (as short as ~ 10 cm), whereas the random DFB fibre laser has extremely weak and long random gratings. Therefore, the mode structure of the conventional DFB fibre laser is defined by the grating, whereas the spatial power distribution in the studied long random DFB fibre laser is mainly defined by the gain.

Considerations based on conventional DFB fibre lasers as building blocks have been used previously for modelling of one-dimensional random lasing with equal scattering centres randomly distributed in amplifying media, assuming that semi-periodic configurations with Bragg-like reflection are responsible for lasing²⁴. In the proposed random DFB fibre laser, the RS feedback is extremely weak and random, both in position and strength of scatterers, so the operation principle is completely different. Moreover, the mean free path length is larger than the characteristic gain length, in complete contrast to the condition for conventional random lasers, which makes the properties of the new lasing scheme considered here rather unique. Nevertheless, near threshold, the temporal and spectral properties of light generated in the random DFB fibre laser are very similar to those in ‘classical’ random lasers. Indeed, in Figs 3 and 4a one can see typical stochastic temporal and spectral behavior, with characteristic spectral peaks generated at random wavelengths, and a non-stationary gain saturation that can be treated as generation of and interactions between extended spatial modes, similar traits to those observed in random lasers.

The most remarkable difference in random lasers is that the increase of the pump power well above threshold leads to stabilization of the generated radiation both in the temporal and the spectral domains (Figs 3, 4b). In the case of homogeneous gain saturation, the single mode of a passive resonator, with a frequency corresponding to the maximum gain with the longest lifetime (that is, the strongest reflection of the grating), should theoretically dominate over all other modes due to gain saturation. However, in reality, such a mode is surrounded by a multitude of overlapping ‘leaky’ modes of the passive resonator, with resonance widths larger than the spacing between them. Therefore, in the ‘active’ resonator, nonlinear interactions lead to frequency mixing, resulting in collective mode formation. Within its relatively narrow linewidth, this effective mode consists of the nonlinear coupled modes of the passive resonator. Formation of the effective mode in the active

cavity is similar to the formalism introduced in ref. 25, where the generated radiation is treated in a new set of modes with constant flux different from the modes of passive resonators. In our laser, the longitudinal field distribution shown in Fig. 1—an effective spatial mode with a maximum at L_{RS} near the fibre output end—is formed as a result of a specific gain/loss profile and nonlinear mode coupling. The impact of multiple nonlinear interactions between the modes of the passive resonator might be described by the weak wave turbulence theory formalism²⁶, as in the ultralong fibre lasers with FBG cavities having closely set modes²¹. A qualitative scenario for the formation of a narrow stable spectrum is the following. The initial unstable components generated at threshold by the combined effect of SBS and RS (refs 17–19) in the pulsed few-pass regime become engaged with increasing power in nonlinear interactions (multiple four-wave mixing processes), leading to a broader spectrum. As a result, the power spectral density becomes lower than the SBS threshold, leading to suppression of the SBS process. Nevertheless, the resulting spectrum is narrow enough (compared to the Raman gain profile). Therefore, the very long length of the random RS-feedback based Raman laser results in SBS suppression due to nonlinear effects, thus providing its principal difference from the previously studied SBS-based lasing with RS feedback¹⁹.

Discussion

The lasing provided by weak random distributed feedback in an amplifying fibre waveguide medium constitutes a new class of laser—the random distributed feedback fibre laser. To the best of our knowledge, this is the first time that stationary lasing has been achieved in a standard telecommunication fibre span using random distributed feedback only, without any point-action or regular distributed reflectors. In contrast to classical random lasers, the random DFB fibre laser delivers well-confined stable laser radiation in a narrow bandwidth similar to conventional lasers. Note that stationary Raman lasing in the cavity, formed by Rayleigh scattering feedback and point reflectors (FBG-based), has recently been reported in ref. 27, providing a narrow spectrum following the FBG reflection bandwidth. The system is proposed for remote sensing with FBGs.

The developed laser scheme is also promising for a variety of applications. For example, the output radiation may be wavelength-tunable²⁸ by simple adjustment of the pump laser wavelength. Applying a distributed chain of pumping sources, a cascaded random DFB laser system might be implemented. The random distributed feedback may also be combined with one (or several) FBG selecting specific wavelengths, and injection locking also seems to be feasible. All these regimes may be realized in transmission fibre lines and applied in long-haul telecommunications^{15,22,29}. Our results also open up the possibility of applications of random DBF lasers in sensing, for example in phase-sensitive time-domain reflectometry based on RS (ref. 30) due to their high sensitivity to the environment and long reach.

Conclusion

The demonstrated random DFB fibre lasers represent a new exciting field of research that brings together such diverse areas of science as laser physics, the theory of disordered systems, fibre optics and nonlinear science. We believe that our results might open up an entirely new area of research, paving a new way to studies of wave transport and localization in disordered media. We anticipate that new fundamental science, as well as new applications and technologies, will emerge from further development of the concept.

Received 30 August 2009; accepted 20 December 2009; published online 7 February 2010

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Acknowledgements

The authors acknowledge support from the Engineering and Physical Sciences Research Council (EPSRC), The Royal Society, the Russian Ministry of Science and Education and the Spanish Ministry of Science and Innovation (grant no. TEC2008-05791).

Author contributions

S.K.T. initiated the study. A.E.E., S.J.K., D.V.C. and V.K. assembled the set-up and performed the measurements. E.V.P., S.K.T. and J.D.A. conducted the analytical analysis. J.D.A. conducted the numerical simulations. S.K.T., S.A.B. and P.H. guided the theoretical and experimental investigations. S.K.T., S.A.B., A.E.E., D.V.C., J.D.A., P.H. and E.V.P. analysed data. S.K.T. and S.A.B. wrote the manuscript.

Additional information

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