Random Distributed Feedback Fiber Laser

Sergei K. Turitsyn

Photonics Research Group, School of Engineering and Applied Science, Aston University, Birmingham B4 7ET, UK
e-mail: s.k.turitsyn@aston.ac.uk

Abstract: I will overview our recent results on ultra-long lasers and will discuss the concept of a fiber laser with an open cavity that operates using random distributed feedback provided by Rayleigh scattering amplified through the Raman effect.

OCIS codes: (140.3550) Lasers, Raman; (290.5870) Scattering, Rayleigh

1. Introduction

Lasers are normally considered as sources of coherent light. However, an ultra-long laser cavity implemented in optical fiber can also be thought of as a special type of transmission medium. Such an ultra-long resonator (which can have a length scale of hundreds of kilometres) is not only an exciting new physical system, but it might also lead to a radical new outlook on the transmission of information. The formation of an effective laser cavity for the pump waves in a transmission fiber span can improve the performance of distributed Raman amplification making possible an efficient cascaded pump delivery and it can also provide for a very low power excursion (quasi-lossless) of the optical signal [1-7]. The length of the resonator is one of the fundamental laser characteristics that define the properties of the emitted radiation. In particular, cavity length determines the spectral spacing between longitudinal modes and thus, the frequency comb of the output radiation. In mode-locked lasers, the length of the resonator is an important design parameter that defines the repetition rate of generated pulses and their per-pulse energy. Higher per-pulse energy in mode-locked lasers (at the same average power of radiation) may be achieved by the extension of the laser cavity, since pulse energy is directly proportional to the round trip time and the total optical path, while the repetition rate is inversely proportional to the resonator length. Single pulse generation with an ultra-low rate mode-locked temporal comb was recently demonstrated in fiber lasers with several km long resonators [8,9]. Despite extraordinary advances in laser science, only recently have the fundamental limits of laser cavity length become an area of exploration [4-10]. In our recent works [6,10] we have studied physical mechanisms that restrict the boundless increase of a fiber laser cavity. There are two key physical phenomena that critically impact the increase of the Raman fiber laser cavity length: four-wave mixing induced optical wave turbulence [7,11] and Rayleigh back scattering (RBS). We demonstrated that in the ultra-long CW Raman fiber laser both effects influence the mode structure and this interplay between the two mechanisms can result in “modeless” spectra at some power levels. By operating close enough to the threshold limit, we have been able to clearly resolve cavity modes up 270 km [6]. The length of laser with a resolvable mode structure is limited not solely by nonlinear interactions between the modes, but also by RBS, which becomes increasingly important with increasing resonator length. Multiple random reflections of forward radiation inside the transmission fiber itself play the role of a distributed mirror. Due to the random character of such reflections along the resonator, they diffuse the effective cavity length parameter forming multiple effective resonators of randomly varying length, leading to the overlapping of modes and creating modeless radiation. The concept of random lasers exploiting multiple scattering in amplifying disordered media to generate coherent light has attracted a great deal of attention in recent years [12-17]. We have demonstrated in [10] a new type of laser with an open cavity, based on RBS in a long fiber span which is amplified through the Raman effect. The fiber 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 those of regular lasers.

2. The concept and parameters of experiments

The concept of the Rayleigh-Raman distributed feedback fiber laser operation is schematically presented in Fig. 1. Photons propagating in a long fiber span are coherently scattered by random refractive index inhomogeneities. Most of the scattered photons leak out of the fiber core. Only small fraction of them are backscattered and guided by the fiber. Two pump waves coupled in the centre at Z=0 provide distributed Raman gain along the fiber span. The backscattered guided photons can be amplified if the total the gain is larger than the loss level, which is fulfilled for all points $|z|<L_{RS}$. As a result, two forward and backward propagating waves are generated.

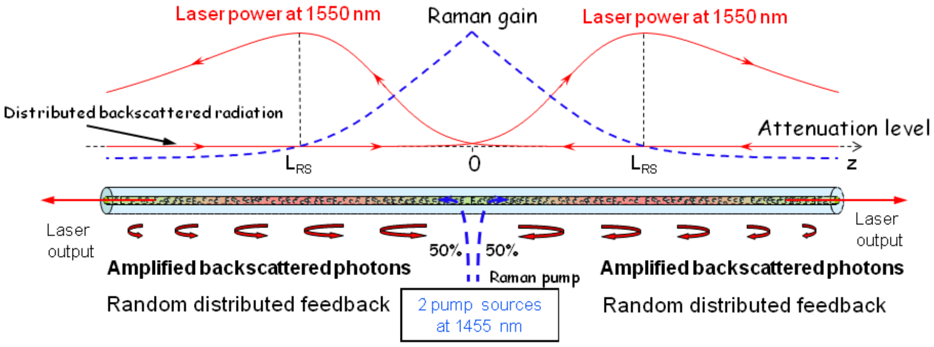

Fig. 1. Principle of operation of random distributed feedback fiber laser. The numerically calculated laser power distribution (solid line) and Raman gain (dashed line) are shown on the top.

The laser medium is a conventional optical fiber (of total length L=83 km in this experiment) with a loss coefficient ~ 0.045 km^{-1} (0.2 dB/km). The backscattering coefficient, i.e. the part of the scattered radiation which is scattered back into the core of the fiber waveguide per unit length is as small as $\varepsilon_{1550} \approx 4.510^{-5}$ km^{-1}. Therefore, the total backward radiation within the fiber is negligibly small (<0.1%) even in a ~100km long passive fiber. However, the situation is dramatically changed when the scattered radiation is amplified. The amplification is implemented by coupling two equal power 1455 nm pump waves into the centre of the fiber in opposite directions thus providing distributed Raman gain with the coefficient g_R ~ 0.39 km^{-1}W^{-1} at 1550 nm, shifted relative to the pump wavelength in accordance with the typical Stokes shift of ~13 THz. The Raman gain for the 1550-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 fiber where the generated radiation as well as the backscattered radiation, are amplified. At $|z|> L_{RS}$ the generated power is attenuated before leaving the fiber. Angled cleaves were used at the fiber end facets to eliminate reflections and ensure that the feedback was due only to the randomly distributed scattering.

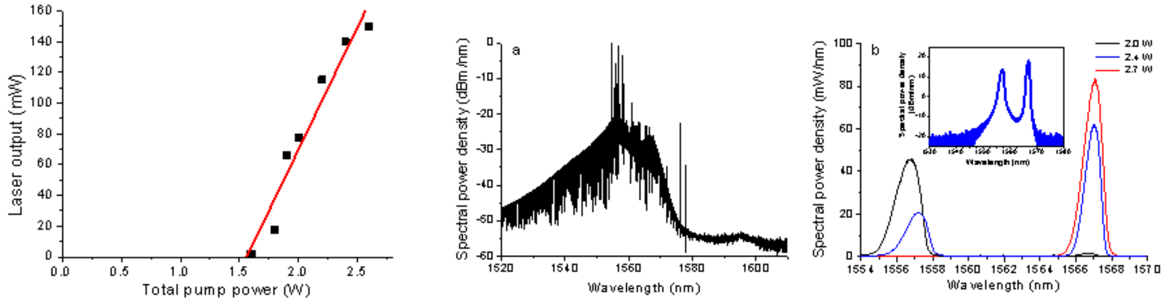

Fig. 2. (left) Random DFB fiber laser power from right output fiber end as a function of the total input pump power. (right) Spectra of generated radiation: a) Laser spectrum near the lasing threshold in the non-stationary regime. b) Laser spectra well above threshold in the CW regime at different total input pump power levels. Insert shows the log-scaled output spectrum at 2.4 W pumping.

Figure 2 (left) demonstrates lasing with a threshold pump power of ~1.6 W and a typical linear growth of the generated output power above the threshold. An output power as high as 150 mW was observed from each (left and right) fiber 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 the threshold (Fig.2 middle) the Raman gain profile is saturated over a broad range while stochastic pulses are generated at random frequencies. Above threshold (Fig. 2 right) narrow spectra are generated with the ASE suppression of ~35 dB.

3. Theory and discussions

We now estimate at what cavity length the effect of the Rayleigh back scattering becomes comparable with the impact of a fiber Bragg grating (FBG) with reflection R located, say, at the right edge of the cavity. From the averaged power equations for the pumping waves $P_p^{\pm}$ and the generated Stokes waves $P_s^{\pm}$ (+/- denots the forward/backward propagation) one can estimate the power that is returned back to the left edge of the cavity:

$$P_s^-(0) \approx RP_s^+(0)\exp[-\alpha_s L + g_R \int_0^{L/2} P_p(s)ds] + \varepsilon_{1550} P_s^+(0) \int_0^{L/2} \exp[-2\alpha_s z + 2g_R \int_0^{z} P_p(s)ds]dz$$

Here L is the total cavity length. The first term in the r.h.s. corresponds to the standard cavity radiation reflected by the second FBG, the second term represents the accumulated effect of the backscattered radiation. The relative impact of these two effects can be characterized by the function:

$$r(L,P_p) = P_s^-(0)_{FBG} \,/\, P_s^-(0)_{RS} \approx R\times\exp[-\alpha_s L + 2g_R \int_0^{L/2} P_p dz]/\{\varepsilon_{1550}\int_0^{L/2}\exp[-2\alpha_s z + 2g_R\int_0^{z} P_p(s)ds]dz\}.$$

The impact of the RBS on laser operation becomes critically important when its contribution to the balance of gain and loss in the cavity is compared to the effect of reflections from FBGs. For random RBS feedback the numerically calculated threshold tends to a constant value for long lengths and increases abruptly at $L<2L_{RC}$ ~70 km, in full agreement with the theoretical estimate. The threshold power for an FBG cavity P_{th}^{FBG} grows linearly with its length L, and at some point should exceed the threshold for RBS-based lasing. Thus, at a certain cavity length the Rayleigh scattering becomes critically important even in standard laser schemes with FBG-based reflectors. Numerical simulations show that a cavity longer than some critical length (L_{cr} ~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, $P_{th}^{FBG} \approx P_{th}^{RS}$. For the laser without FBGs – pure random distributed feedback laser, the threshold condition is defined by the integral gain/loss balance equation at the "round-trip" within a fiber with the effective "distributed mirror", formed by the RBS: $\varepsilon_{1550}\int_0^{L/2} dz\exp[-2\alpha z + 2g_R\int_0^{z} P_p(s)ds] = 1$. Using the standard saddle-point approximation one can derive [10] that the threshold is about 0.8 W for each arm, which agrees with the observed experimental threshold of 1.6 W.

In conclusion, the lasing provided by weak random distributed feedback in an amplifying fiber waveguide medium constitutes a new class of laser – the random distributed feedback fiber laser that can find applications not only as a source of light, but also as a medium for distributed sensing and communications.

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