Narrow-band generation in random distributed feedback fiber laser

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Abstract: Narrow-band emission of spectral width down to ~0.05 nm line-width is achieved in the random distributed feedback fiber laser employing narrow-band fiber Bragg grating or fiber Fabry-Perot interferometer filters. The observed line-width is ~10 times less than line-width of other demonstrated up to date random distributed feedback fiber lasers. The random DFB laser with Fabry-Perot interferometer filter provides simultaneously multi-wavelength and narrow-band (within each line) generation with possibility of further wavelength tuning.

OCIS codes: (140.3510) Lasers, fiber; (140.3490) Lasers, distributed-feedback; (290.5910) Scattering, stimulated Raman; (290.5870) Scattering, Rayleigh.

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1. Introduction

Random lasers refer to a unique class of lasers where a classical resonator is replaced by randomly distributed scattering centers. Lasing in such a system with "non-resonant feedback" was first demonstrated by Ambartsumyan et al, where the fully reflecting mirror of a ruby laser was replaced with a rough surface [1]. The field saw a resurgence in activity after the development of pulsed lasers, eventually leading to realization of various random lasing configurations [2–4]. The most common form of the random laser is the powder form, where the active medium itself helps to scatter the emitted radiation [5]. Other forms include colloidal suspension of scattering centers in an active medium [6], nanowires [7] and polymers [8]. The simplicity of realization of random lasers gives them an upper hand over conventional lasers. In general, the drawbacks of such systems are the requirement of high peak powers, low efficiency due to small active areas with poor confinement and low directionality, and more importantly, cumbersome or almost no control over the spectral properties of the emission.

To address confinement and directionality issues, a suspension of TiO_2 particles in a rhodamine-G solution was inserted into hollow core optical fiber [9]. This resulted in an improvement in the efficiency by two orders of magnitude when compared to random lasing realized in bulk random media due to fiber guiding properties. In fibers, a random feedback can be also provided by strong scattering on conventional fiber optic mirrors – fiber Bragg gratings (FBGs) placed (in spectral domain) in a random way by using a number of different gratings [10,11] or introducing randomly incorporated phase errors in a single FBG [12].

Recently, a concept of a new type of a random laser operating via extremely weak random scattering in a single mode fiber has been proposed and experimentally demonstrated [13]. The random distributed feedback (DFB) is provided via backward random Rayleigh scattering amplified through the Raman effect in a long (tens of km). While the threshold of this laser is relatively high, the efficiency was noted to be quite comparable to existing CW lasers [13,14]. A number of different random DFB fiber laser configurations are realized up to date [15–36]. In particular, random DFB fiber lasers can be multi-wavelength [18–20], tunable [21,22], can operate in different spectral bands [23,24] and provide cascaded operation at higher Stokes components [23,25]. In terms of applications, random DFB fiber lasers are promising for sensing [27–31,34] and telecom applications [32,33]. In particular, the use of the random DFB system as a sensor in conjunction with a Brillouin-OTDR system was also demonstrated [31]. The random DFB fiber laser has a lower noise figure when compared to a bi-directional 1st order and 2nd order Raman pumping configurations [32,33]. The concept of random DFB fiber laser is further developed by implementing a stimulated Brillouin scattering (SBS) instead of Raman scattering [34,35].

In all random DFB lasers demonstrated up to date, the laser radiation is rather broad having a typical spectral width of 1 nm and more. It is of practical interest to suppress the linewidth of the random DFB laser. In the present work, lasing of spectral widths down to 0.05 nm is demonstrated in the random DFB system by use of narrow FBG or fiber based Fabry-Perot filter.

2. Experimental results

2.1 The laser design

Figure 1 shows a schematic diagram of the experimental setup. Two spans of 40 km standard Corning SMF 28 fiber were pumped from the central point by two Raman fiber lasers at 1455 nm. Raman gain has a maximum near 1550 nm in this case. Above the generation threshold, the random generation owing the random distributed Rayleigh feedback is started.

To obtain the narrow-band generation, spectral filters are used. Two types of filters are used in this work: FBG or fiber-coupled Fabry-Perot filter (FFP). The FBG has a Gaussian profile, with line-width 0.05 nm and centered around 1550.5 nm. The FFP filter has a passband at 1552.7 nm, finesse 486 and a free spectral range 623.60 GHz. This corresponds to a spectral width of 10 pm for every FFP transmission pike. To enable using the filter in the laser and to preserve the random feedback at the same time, a unidirectional circulator configuration is employed. This also provides isolation when the FFP is used. The radiation propagating from left fiber end to right fiber end is bypassed through the spectral filter allowing selective gain only within the reflection bandwidth of the filter. The radiation propagating from the right fiber end to the left fiber end freely passes via the upper branch.

The non-uniform longitudinal power distribution in the random DFB fiber laser allows us to use low-power handling filter (like FFP) to manage properties of the high power (~1 W) random generation. Indeed, the power at the central point of configuration is sufficiently lower than maximum generated power [13,14,36]. In our case the power at filter position is always lower than 10 mW, while generated power at maximum is of order of 1 W.

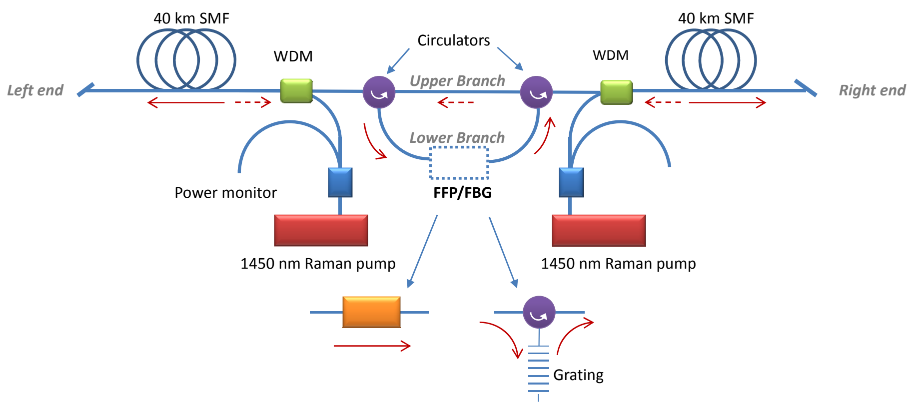

Fig. 1. Experimental configuration of the narrow-band random DFB laser. The red arrows indicate the direction of propagation of laser radiation within the cavity. A spectrally selective element is inserted in the lower branch.

2.2 Emission characteristics

Firstly, we study the system with FBG used as a spectral filter. Generation initiates beyond a marked threshold, and the generation power increases almost linearly with the pump power (Fig. 2(a)). Till the pump power of 1.2 W, the generation spectral width is almost constant at level around 0.05 nm and follows the spectral width of used FBG (Fig. 2(b)). So narrow-band generation in a random DFB fiber laser is achieved. Note that the minimal spectral achieved in the configuration without spectral filter is 0.5 nm. Beyond 1.2 W of pump power, the spectrum becomes to be broader than spectral filter. Moreover, the generation properties become asymmetric: the spectral broadening is much more pronounced at the left output of the laser, where the broadest spectrum has a width of ~0.3 nm (being still narrower than in the case of random DFB fiber laser without any spectral filters). The spectrum width of the generation emitted from the right end of the system is always below 0.1 nm. Note that in the case of the pure random DFB system which does not employ any spectral filters, the output characteristics are symmetric [13]. We have specially checked that the observed asymmetry (power and spectral) in outputs is reversed if the filter is moved to the upper branch, which rules out any effects arising due to pump asymmetry.

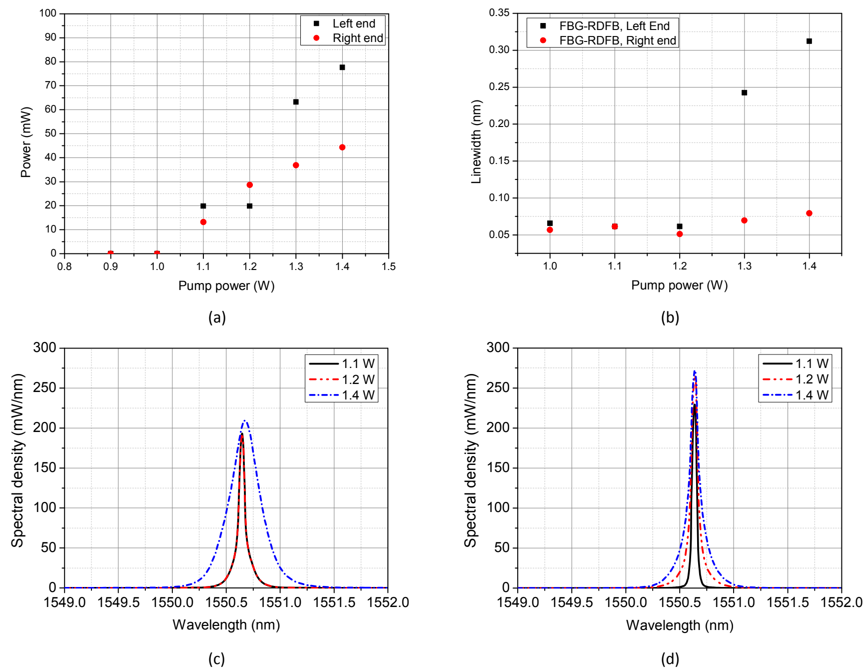

Fig. 2. Generation properties of random DFB fiber laser with a narrow-band FBG as a spectral filter: (a) Output power (b) The full linewidth and half maximum (FWHM) depending on pump power. (c,d) Optical spectra at different pump power level from left (c) and right (d) outputs.

Similar results are obtained with FFP as a spectral filter (Figs. 3(a), 3(b)). The narrow-band generation is generated. The observed line-width is below the 0.02 nm OSA instrument function. As pump power increasing, the spectrum becomes broader than the spectral width of FFP filter and asymmetry generation properties emitted from the left and right outputs of the system arises. As the free spectral range of the FFP is smaller than the Raman gain profile spectral width, multiple lines are generated simultaneously (Fig. 3(b)), each of them being narrow-band itself. Note that the presented configuration provides a straight-forward and easy way to obtain a narrow-band multi-wavelength and simultaneously tunable generation by using narrow-band tunable FFP filter. The separation between channels can be controlled in precise way by managing FFP spectral properties.

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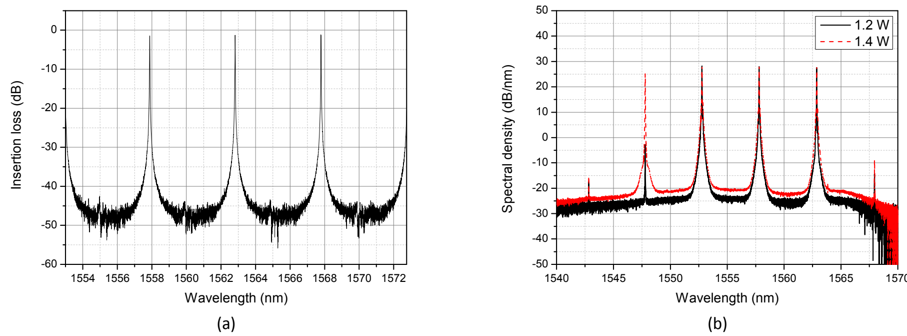

Fig. 3. Generation properties of random DFB fiber laser with a narrow-band FFP as a spectral filter: (a) Transmission profile of the FFP (b) Multiwavelength narrow-band generation observed at the right output.

3. Discussion

The generated spectra are different along the different points in the cavity for both FBG based and FFP based configurations (Figs. 4(a), 4(b)). While the FBG/FFP presents a well filtered signal for the fiber span on the right, the backscattered signal from the right contains a significant Brillouin scattered component (0.08 nm shifted from the main spectral peak), as observed in the upper branch. As the generation power along the fiber could be as high as 1 W providing high enough nonlinearity, the four wave mixing (FWM) between different SBS components could be initiated. In addition, as the random DFB fiber laser is mode-less, i.e. comprising numerous very close-spaced spectral components [13], the radiation even in so narrow bandwidth as 10 pm has to be partially coherent. So, in addition to the SBS initiated FWM, the self-phase modulation of partially coherent radiation [37] within each SBS component could be pronounced. Depending on phase stochastization mechanism, different spectral broadening laws (linear [38] or square-root [39,40]) could be realized. The question of exact spectral broadening law in narrow-band random DFB fiber laser should be further investigated.

The narrow-band random DFB fiber laser could be a good candidate to investigate temporal and statistical properties of random fiber lasers. Indeed, the question of temporal and statistical properties of quasi-CW partially coherent lasers is of general interest in past years [41–46]. There is no up to date any experimental study of temporal or statistical properties of random DFB fiber lasers based on Raman scattering. However, it is known that random Rayleigh scattering could change sufficiently temporal and statistical properties of SBS lasers [47]. Having narrow-band generation within 10 pm (around 1 GHz) bandwidth, the temporal and statistical properties of the laser could be investigated in real-time using conventional oscilloscopes directly without using spectral filtering techniques [46] or indirect methods of measuring fast intensity fluctuations [48]. The result of this investigation will be published elsewhere.

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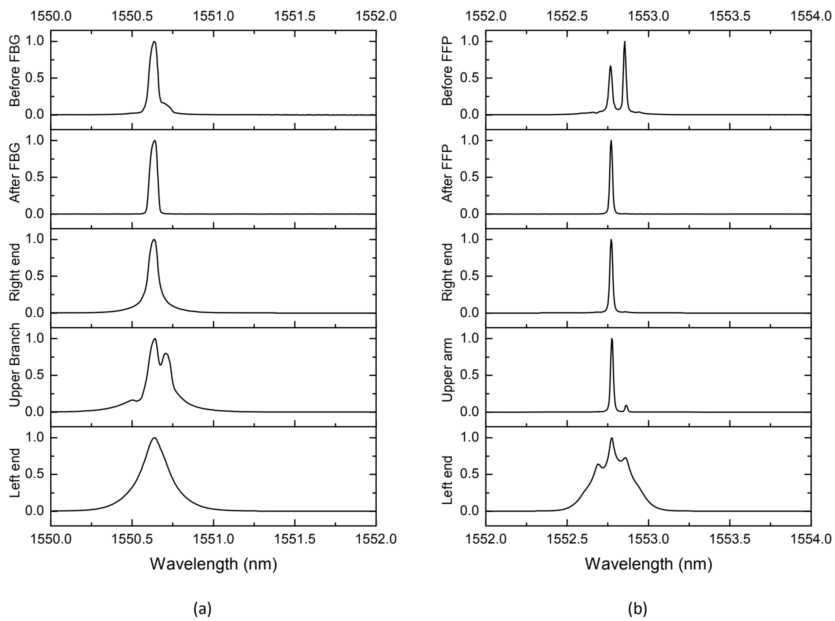

Fig. 4. Optical spectra at different locations in a random DFB fiber laser with (a) FBG and (b) FFP filter.

4. Conclusions

To conclude, for the first time narrow-band generation of random DFB fiber laser has been demonstrated using narrow-band spectral filter in the random laser. Despite the fact that there is almost no generated power in the central part of the laser where the filter is placed, introducing the narrow-band filter provides laser generation with a line-width down to 0.05 nm being 10 times narrower than minimal achieved line-width in random DFB fiber lasers without spectral filters. The random DFB laser with FFP provides multi-wavelength and narrow-band (within each line) generation. At low power, the generation spectrum bandwidth is limited by the spectral filter bandwidth, but not by the Raman gain spectral profile. At higher pump power, the nonlinear spectral broadening affects the spectral shape and width due to cooperative processes of stimulated Brillouin scattering, self-phase modulation and four wave mixing. The presented laser configuration provides the opportunity of obtaining extremely narrow line-width radiation upon suitable optimization and simultaneous tunable and multi-wavelength operation.

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