Room Temperature Multifrequency Erbium-Doped Fiber Lasers Anchored on the ITU Frequency Grid

Antoine Bellemare, *Member, OSA*, Miroslav Karásek, Martin Rochette, Sophie LaRochelle, *Member, OSA*, and Michel Têtu, *Senior Member, IEEE, Member, OSA*

***Abstract*—Room temperature multifrequency erbium-doped fiber (EDF) lasers anchored on the ITU frequency grid and using frequency periodic filters are presented. The multifrequency operation is demonstrated both theoretically and experimentally by adding a frequency shifter in the ring cavity to prevent steady-state laser operation and single-frequency oscillation.**

***Index Terms*—Erbium, optical fiber source, wavelength-division multiplexing (WDM), optical communication, ITU frequency grid.**

I. Introduction

ABSOLUTE frequency calibrated multifrequency sources are required for frequency referencing in dense wavelength-division-multiplexing (DWDM) systems. They find applications in components testing (e.g., chromatic dispersion measurements [1]) or as transmitters. The requirements for multifrequency sources include a large number of peaks (channels) over a broad bandwidth, high output power uniformly distributed over the channels and precise positioning on the ITU frequency grid [2], [3]. Meeting all the aforementioned requirements is a very challenging task. Various approaches have been suggested and experimentally tested to achieve concurrent lasing at several wavelengths in both semiconductor and fiber lasers.

A straightforward approach is to combine into a single fiber the output power from an array of single wavelength lasers [4]. Channel spacing regularity can be improved using multiple wavelength semiconductor lasers based on an array of physically separated gain media with lasing wavelengths determined by diffraction gratings [5], [6] or waveguide grating routers [7].

In order to achieve simultaneous multiple wavelength operation in an erbium-doped fiber (EDF) laser, the predominantly homogenous line broadening at room temperature must be overcome. Otherwise, the gain will be clamped by the resonator loss at only one lasing frequency and separate gain media have to be used for each wavelength channel [8]–[10]. In [11]–[14] a single erbium-doped fiber (EDF) was cooled in liquid nitrogen (77 K) to reduce the homogeneous broadening and cross-gain saturation effects in the fiber therefore promoting multiwalength operation.

Early proposals for room temperature operation of multiwavelength fiber laser using a single standard EDF showed the feasibility but were not very efficient [15], [16]. Later, Hübner *et al.* [17] showed that an efficient multiwavelength source can be obtained by the photoinscription of many DFB Bragg gratings in a single EDF. The use of special fibers has also led to elegant designs. An erbium-doped twincore fiber has been used in [18] to provide an inhomogeneous gain medium through macroscopic spatial holeburning. In their multiwavelength fiber laser, Poustie *et al.* [19] used a multimode fiber to build a spatial mode beating filter with a frequency periodic response. Other methods, like optical feedback [20], [21] and nonlinear gain in optical fiber have also been exploited. For example, multiple wavelength operation of a hybrid Brillouin-erbium fiber laser has been described in [22].

Room temperature multifrequency operation in a single EDF ring laser has been reported in [23], [24] by adding a frequency shifter in the cavity to prevent steady-state oscillations. Initialy [23], it was believed that the amplified spontaneous emission (ASE) power generated in the EDF and circulating in the ring resonator was repeatedly sliced by the periodic bandpass filter and frequency shifted by an acoustooptic frequency shifter (AOFS) leading to a multifrequency incoherent source. However, we recently showed that this source is in fact a laser [24].

In this paper, we study the realization of room temperature multifrequency EDF lasers (MF-EDFL) anchored on the ITU frequency grid using various frequency periodic filters such as Fabry-Perot etalons and sampled fiber Bragg gratings (SBG). Multifrequency operation is obtained by adding a frequency shifter in the ring cavity to prevent steady-state lasing and single-frequency oscillation. The operating principle of this laser is also studied by numerical simulation. Further calculations highlight the potential for uniform wideband output power operation. The MF-EDFL's are characterized in terms of bandwidth, output power, power spectrum flatness, and frequency precision with respect to the ITU frequency grid. The frequency shifter approach does not require liquid nitrogen cooling; a major advantage in the realization of a practical

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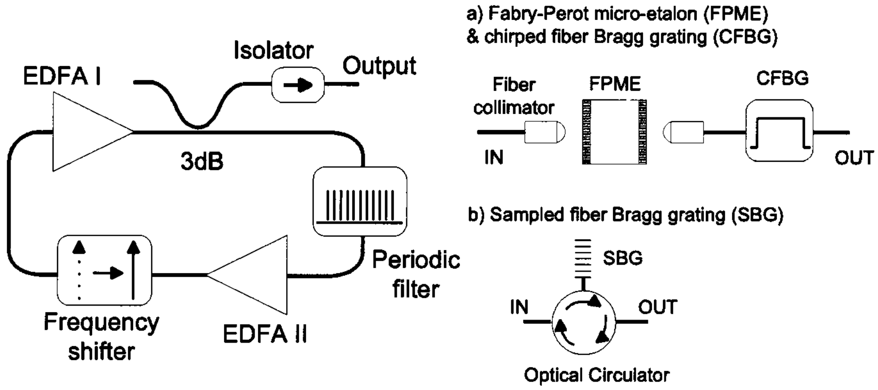


Fig. 1. Schematic diagram of the MF-EDFL.

multifrequency laser source. These multifrequency lasers also have the advantage of being built using standard EDF and other readily available components.

II. Principle of Operation

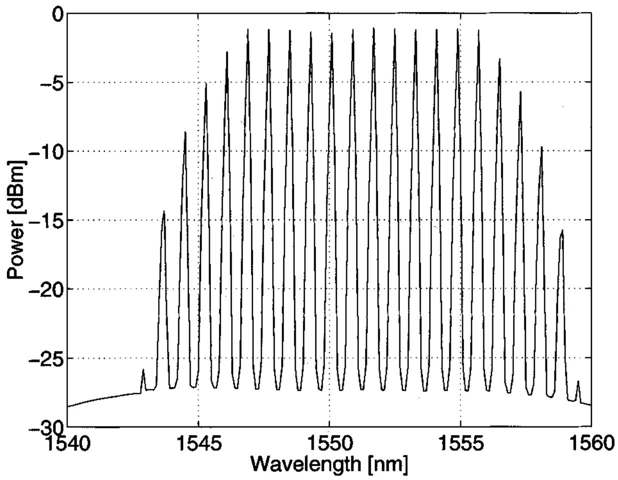
Fig. 1 shows the general schematic diagram for the MF-EDFL's presented in this paper. First, the emission from the EDFA's output is filtered in the fiber feedback loop by a bandlimited frequency periodic filter. Two types of bandlimited frequency periodic filters are studied in this paper. The first filter is a 100-GHz Fabry–Perot micro-etalon (FPME) cascaded with a chirped fiber Bragg grating (CFBG) bandpass filter limiting the FPME band. The second filter used is a 100-GHz sampled fiber Bragg grating (SBG) [25]. These filters will be described further in Section IV. Following the periodic filter, the light is frequency translated by 100 MHz using an AOFS. Therefore the feedback power is shifted to a neighboring frequency in each round-trip, homogeneous line broadning of the EDF is suppressed and single wavelength steady-state lasing is prevented. Futhermore, there is no specific requirements on the AOFS frequency translation since shifts in the 40–60 and 90–110 MHz range have yielded successful multifrequency operation. This is because the multifrequency operation does not require the cavity to be modelocked. Finally, the usable signal is collected, using a 3-dB coupler, just after erbium-doped fiber amplifier (EDFA) I for optimum output power.

III. Modeling of the MF-EDFL

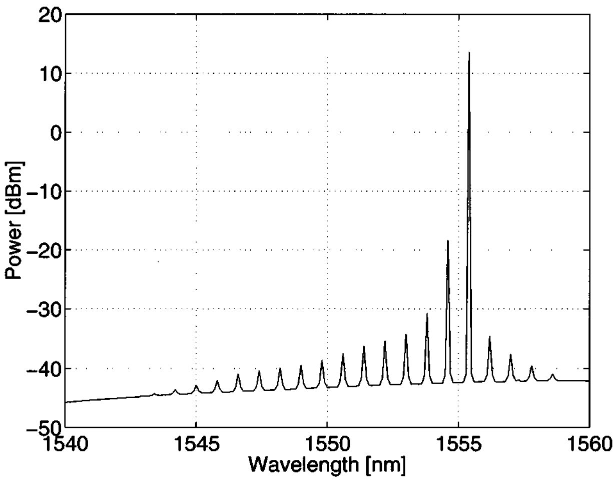
The performance of the MF-EDFL has been simulated using a space and frequency resolved numerical model. The model is based on a homogeneously broadened three-level approximation of the erbium ion and has been described in detail in [26]. An iterative solution of rate equations and propagation equations for the pump and for both the forward and backward propagating spontaneous/stimulated emission powers is implemented using a fourth-order Runge–Kutta routine. The numerical model follows the experimental configuration of the MF-EDFL shown in Fig. 1, i.e., the forward propagating power generated in EDFA I is filtered by a band-limited frequency periodic filter and amplified by EDFA II. When traveling through the ring resonator, spectral components of the signals in EDFA II are frequency shifted each time by one frequency slot (0.1 nm) during the iteration process. Even though this frequency shift is much larger than the shift used in the experiments, it is still valid to demonstrate the principle of operation of the MF-EDFL. The backward propagating ASE is suppressed by optical isolators placed in each EDFA. In the analysis, a typical Lucent Technology EDF has been considered.

All emission and absorption cross sections included in the model are spectrally resolved. The spectral region from 1450 to 1650 nm has been subdivided into 2000 slots of $\delta\lambda = 0.1$ nm. The frequency periodic filter has been simulated by a superposition of Gaussian bandpass filters spaced by 0.8 nm with a 3-dB bandwidth of 0.15 nm. The transmittance of the first five and last five of the 22 filters peaks has been decreased following a 5-dB/nm slope. The effect of the overall ring resonator losses, gain of EDFA I and II and the number of peaks of the periodic filter on the performance of the MF-EDFL has been investigated.

First, we demonstrate that single-frequency operation of the EDF ring laser is prevented by shifting the frequency of the ASE spectral components in each round-trip through the ring resonator. Fig. 2(a) and (b) shows the power spectrum of the MF-EDFL when the frequency shifter is in or out of operation, respectively. With the frequency shifter on, the resultant effect is the same as if the filtered ASE power fed at the input of EDFA I where amplified/absorbed each time by slightly different emission/absorption cross sections of the EDF. The homogeneous line broadening of the gain media is thus effectively suppressed. Then, if the gain of EDFA I and II and the total ring resonator loss are appropriately selected, the output spectrum can be made flat and similar to the transmittance of the periodic filter. Without frequency shifting, one strong single lasing line develops at $\lambda = 1555.4$ nm, the wavelength with the highest gain. The output power spectra calculated for the MF-EDFL with and without the frequency shifter are in qualitative agreement with the experimental results that will be presented later. The simulations have been performed for the following MF-EDFL parameters—length and pump power ($\lambda_p = 980$ nm) of EDFA I and II: $L_1 = 25$ m, $L_2 = 23$ m, $P_{p1}^- = 50$ mW (backward pumping), $P_{p2}^+ = 30$ mW (forward pumping), frequency shifter loss $\alpha_{\rm shift} = 8$ dB, periodic filter loss $\alpha_{\rm filter} = 8$ dB. The overall ring losses are $\alpha_{\rm ring} = 19$ dB.



(a)



(b)

Fig. 2. Output power spectrum. (a) with a frequency shifter and (b) without a frequency shifter.

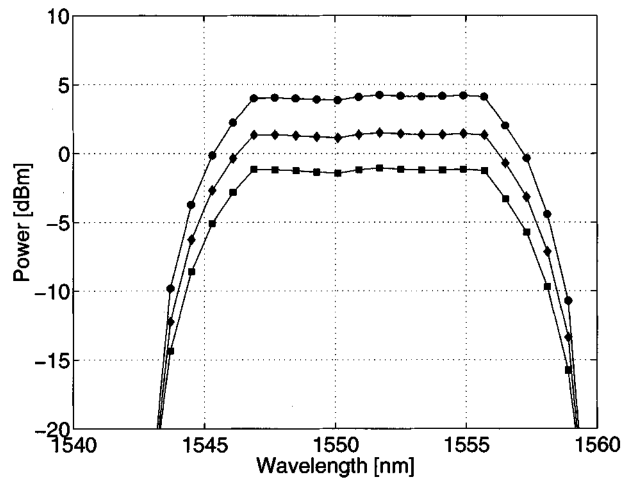


Fig. 3. Envelope output power spectrum for various conditions. ■: $L_{1,2} = 25$, 23 m, $P_{p1,2} = 50$, 30 mW, $S = 8$ dB, $F = 8$ dB. ◆: $L_{1,2} = 20$, 23 m, $P_{p1,2} = 90, 30$ mW, $S = 5$ dB, $F = 5$ dB. •: $L_{1,2} = 30, 10$ m, $P_{p1,2} = 150$, 120 mW, $S = 3$ dB, $F = 3$ dB.

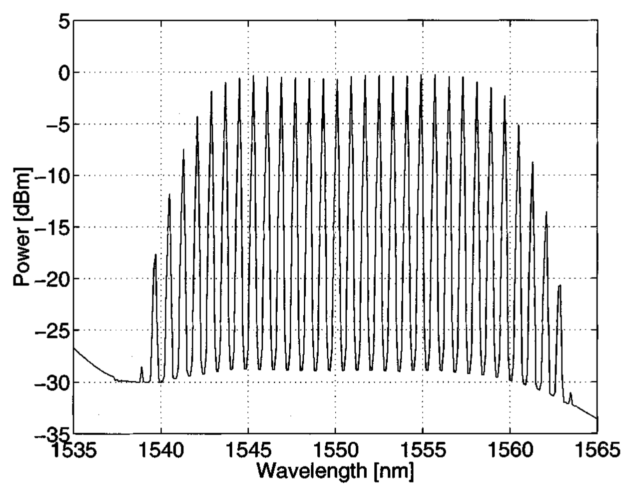


Fig. 4. Output power spectrum for wideband operation.

The above EDFA parameters give small signal gains at 1550 nm and length averaged metastable level populations of $G_1 = 31.8$ dB, $N_1 = 0.862$, $G_2 = 29.6$ dB, and $N_2 = 0.866$.

The output power of the MF-EDFL may be increased if the losses of the frequency shifter α_{shift} and the periodic filter α_{filter} are reduced. In order to maintain a flat output spectrum ($\Delta P_{\text{out}} < \pm 0.2$ dB), the gain of both EDFA's has to be adjusted. The shape of the MF-EDFL output power spectrum has been controlled by varying the length and pump power of both EDFA's. Fig. 3 shows the envelope of the output spectrum when the periodic filter and frequency shifter losses are reduced from the original value of 8 dB to 5 and 3 dB. The output power at the flat part of the spectrum is -1.2, $+1.3$ and $+4.1$ dBm for $\alpha_{\text{shift}} = \alpha_{\text{filter}} = 8$, 5, and 3 dB, respectively.

We have also calculated that the spectral range of the experimental MF-EDFL is limited by the periodic filter rather than by the EDF. When the number of peaks of the periodic filter was increased from 22 to 32, it was still possible to select the EDFA gains G_1, G_2 by varying the lengths and pump powers of individual amplifiers to get a flat output spectrum with $\Delta P_{\text{out}} < \pm 0.6$ dB over 20 peaks. The calculated power spectrum is shown in Fig. 4.

IV. Experimental Results

A. *Fabry-Perot Micro-Etalon Based MF-EDFL*

The first MF-EDFL studied uses a Fabry–Perot micro-etalon (FPME) [27] in series with a gate type chirped fiber Bragg grating (CFBG) band pass filter as shown on Fig. 1(a). The CFBG limits the spectral band of the FPME while rejecting the EDFA's 1.53-μm gain peak. Limiting the spectrum helps to obtain multifrequency operation with significant power. The CFBG has been written with a frequency-doubled Argon laser emitting about 75 mW at 244 nm and a 5-cm long 1525–1565-nm chirped phase mask [28]. The spectral transmission of the CFBG filter is plotted in Fig. 5. The CFBG has one transmission window in the EDFA gain

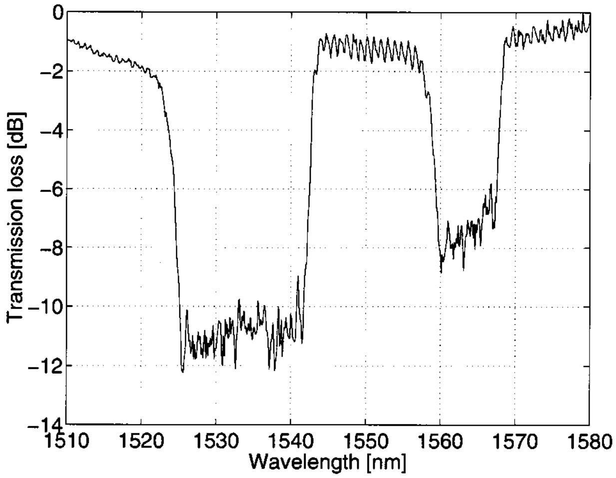


Fig. 5. Spectral transmission of the CFBG bandpass filter.

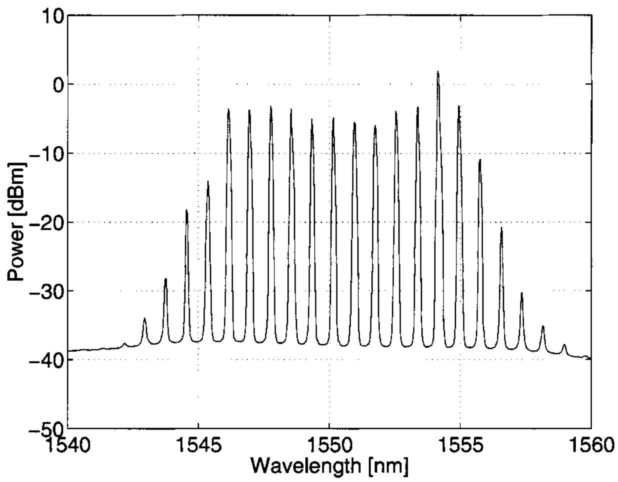


Fig. 6. FPME-based MF-EDFL power spectrum.

band (1520–1570 nm) from 1542.7 to 1558.7 nm with an out of band rejection of 7 to 11 dB. The FPME is a small piece of silica ($\sim 1.5 \times 1.5 \times 1.0$ mm) with dielectric mirrors ($R \sim 60\%$). The FPME has a 99.85-GHz FSR at normal incidence, a finesse of about 6 ($\Delta\nu \sim 17$ GHz) and an insertion loss of 8 dB. Fine tuning of the FPME spectral response is achieved by slightly tilting the etalon.

Single-frequency operation is prevented by the use of a 100-MHz AOFS having an insertion loss of 8 dB. Two EDFA's are needed because the FPME and the AOFS are free-space devices having high insertion losses. With reduced losses, a single gain element would be sufficient. EDFA I is a commercial amplifier providing about 30 dB of small signal gain in the CFBG bandpass while EDFA II is a 20-dB gain in-house built amplifier.

The FPME-based MF-EDFL output power spectrum, measured with an optical spectrum analyzer, is shown in Fig. 6. The source presents 14 peaks which are at least 20 dB over the ASE baseband and 7.8 dBm of total power. The measured peak

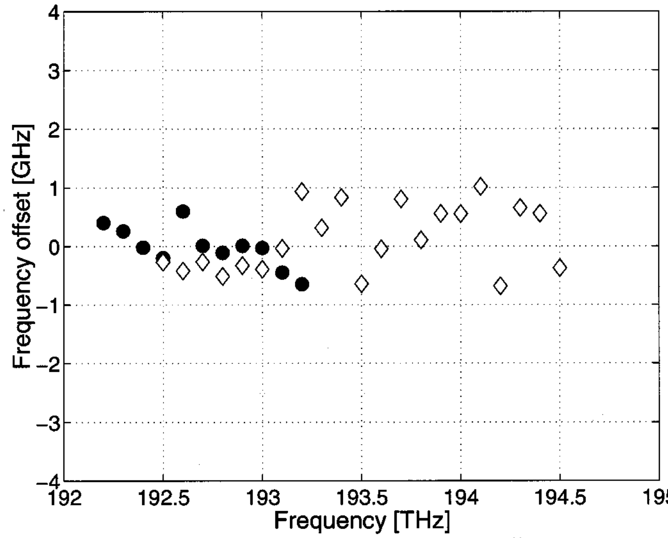


Fig. 7. Frequency offset from ITU grid for the FPME (◇) and SBG (●) based MFEDFL.

linewidths are resolution limited to 0.08 nm (10 GHz) as imposed by the optical spectrum analyzer. The power spectrum is fairly uniform and depends slightly on the AOFS fiber coupling. The smaller peaks on each side are due to the finite edge slope, about 3–5 dB/nm, of the CFBG filter. The occurence of the highest peak around 1554.13 nm is due to a combination of the highest gain of the EDF and the lowest loss of the ring cavity at this wavelength. This coincidence is also apparent in the results of the numerical simulation shown in Fig. 2(b).

Angle tuning the FPME has allowed us to set the peak frequencies on the ITU grid values. Fig. 7 presents the channel frequency offsets from the ITU grid as measured with a 0.001-nm resolution Fourier transform scanning Michelson interferometer. The mean residual offset from the ITU grid is $\overline{\nu - \nu_o} = 0.112$ GHz, the cumulative offset is $\Delta(\nu - \nu_o)/\Delta\nu = +0.035$ GHz/100 GHz (FSR=100.35 GHz) and the standard deviation is $\sigma_{\nu - \nu_o} = 0.562$ GHz. The mean residual offset comes from systematic measurement errors and imperfect channel position setting. The cumulative offset is related to imperfect FSR setting. Finally, the standard deviation is due to random measurement errors and peak to peak frequency spacing fluctuations. It is believed that with reasonable care and increased measurement precision a frequency accuracy of better than ± 0.1 GHz could be achieved.

B. Sampled Bragg Grating-Based MF-EDFL

A second MF-EDFL is built using a SBG as the frequency selective element in the cavity [see Fig. 1(b)]. The SBG was written in an hydrogen loaded B:Ge-codoped fiber. The sampled structure is achieved by overlaying an amplitude mask on the phase mask used in the scanning beam writing technique [29]. The grating is 5 cm long with a sampling period of 1.02 mm and a duty cycle of $\sim$12%. The writing ultraviolet (UV) source is a frequency quadrupled Nd:YAG producing 40 mW at 266 nm. The spectral transmission of the SBG bandpass filter is plotted in Fig. 8. This SBG has fifteen reflection peaks between 1550.15

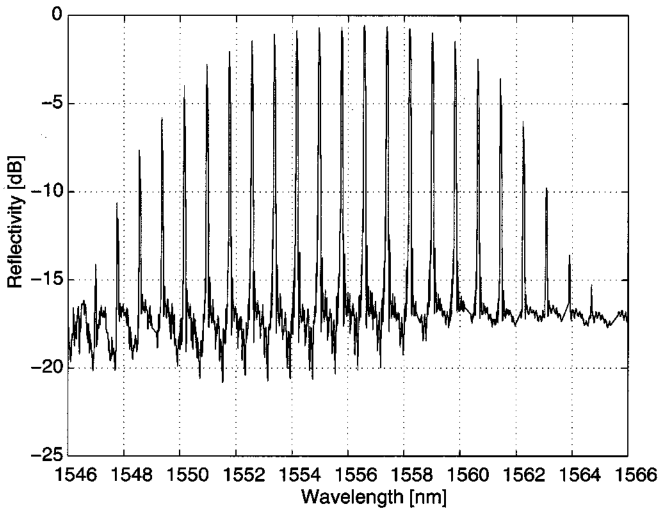


Fig. 8. Reflection spectrum of the SBG filter.

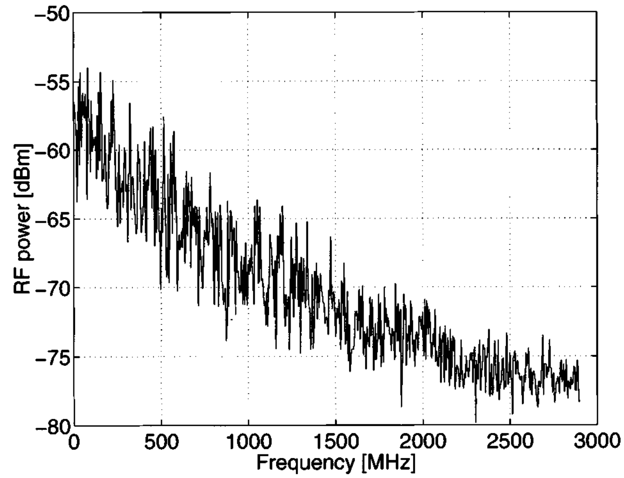


Fig. 10. Self-beating RF power spectrum of the laser.

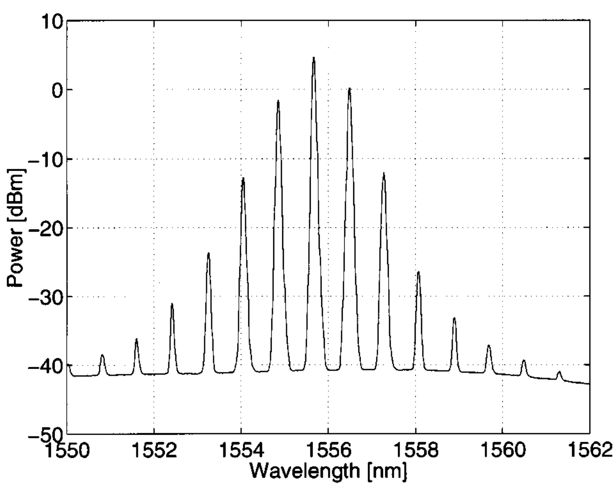


Fig. 9. SBG-based MF-EDFL output power spectrum.

and 1561.45 nm, spaced by nearly 100 GHz (99.90 GHz), each peak having a 3-dB bandwidth of about 7 GHz.

The SBG-based MF-EDFL output power spectrum is shown in Fig. 9. The lasers shows five peaks which are at least 20 dB over the ASE baseband and a total power of 6.8 dBm.

Linewidth measurement of the 1557.34 nm peak, performed with a setup composed of a tunable bandpass filter, a fast photodetector, and an radio frequency (RF) spectrum analyzer, showed (see Fig. 10) that the peak is multimode and a few GHz wide. From Fig. 10 it also apears that the laser output is not pulsed, that fact was latter confirmed with a fast digital sampling oscilloscope. At higher resolution, we observed that the RF self-beating spectrum showed mode structure with cavity modes 2.8 MHz apart. Since the linewidth of the source is narrower than the bandwith of the periodic filter and since the output spectrum shows mode structure we have a confirmation that the source is in fact a laser. It must be noted that the numerous cavity modes are detrimental to the operation of this laser as a transmitter. However, the somewhat low coherence of this laser is advantageous in components testing since it reduces parasitic interference effects.

The frequency offset from the ITU grid in the case of the SBG-based MF-EDFL is indicated by the dots on Fig. 4, the mean residual frequency offset from the ITU-Grid is −0.016 GHz, the cumulative offset is −0.076 GHz/100 GHz (FSR=99.92 GHz), and the standard deviation is 0.355 GHz. The flatness of the power spectrum could be improved by using a sinc-sampled fiber Bragg grating (S-SBG) [30] which has a flat top reflection spectrum. Thus, we propose the use of S-SBG as the bandlimited periodic filter of choice to obtain flat power spectrum and precise peak frequency positioning on the ITU grid [24], [27].

V. Conclusion

In summary, room temperature multifrequency operation of EDF ring lasers anchored on the ITU frequency grid is demonstrated by numerical simulations and experimental results. Single-frequency lasing is prevented by the use of an acousto-optic frequency shifter in the feedback loop. The performance of two band limited periodic filters, a Fabry–Perot micro-etalon cascaded with a chirped fiber Bragg grating, and a sampled Bragg grating are compared. In both cases, better than ±1 GHz frequency accuracy is obtained over a wide frequency range. The FPME offers a broadband coverage but a limiting bandpass filter is required to allow useful power generation (12 peaks in this case). The SBG is intrinsically bandlimited and readily fiber compatible. The SBG-based laser power spectrum flatness could be improved by using a sinc-sampled fiber Bragg grating (S-SBG) instead of a SBG.

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