Periodic and non-periodic frequency selection in an erbium doped fiber laser by silica microdisk optical cavity filters

Sacha Bergeron, Samir Saïdi and Yves-Alain Peter

École Polytechnique de Montréal, Department of Engineering Physics
P.O. Box 6079, Station Centre-Ville, Montréal (QC), H3C 3A7, Canada
**yves-alain.peter@polymtl.ca.*

Abstract: Integrated silica microdisk resonators can be used to create a variety of very high performance spectral filters. These filters can control the spectral emission of an erbium doped fiber laser. By modifying the number and sizes of the microdisks constituting these filters it is possible to produce single wavelength, periodic multi-frequency and non-periodic multi-wavelength fiber lasers. Channel spacing as low as 0.28 nm and non-periodic four wavelength lasers were demonstrated.

OCIS codes: (130.3120) Integrated optics devices; (130.3990) Micro-optical devices; (130.7408) Wavelength filtering devices; (140.3510) Lasers, fiber; (140.3945) Microcavities; (140.4780) Optical resonators; (230.7408) Wavelength filtering devices; (140.3948) Microcavity devices.

References and links

1. A. Bellemare, M. Karasek, M. Rochette, S. LaRochelle, and M. Tetu, "Room temperature multifrequency erbium-doped fiber lasers anchored on the itu frequency grid," J. Lightwave Technol. **18**, 825–831 (2000).
2. J. Cousin, P. Masselin, W. Chen, D. Boucher, S. Kassi, D. Romanini, and P. Szriftgiser, "Application of a continuous-wave tunable erbium-doped fiber laser to molecular spectroscopy in the near infrared," Appl. Phys. B **83**, 261–266 (2006).
3. N. Park and P. Wysocki, "24-line multiwavelength operation of erbium-doped fiber-ring laser," IEEE Photon. Technol. Lett. **8**, 1459–1461 (1996).
4. X. Dong, S. Li, K. Chiang, M. Ng, and B. Chu, "Multiwavelength erbium-doped fibre laser based on a high-birefringence fibre loop mirror," Electron. Lett. **36**, 1609–1610 (2000).
5. Q. Mao and J. Lit, "Switchable multiwavelength erbium-doped fiber laser with cascaded fiber grating cavities," IEEE Photon. Technol. Lett. **14**, 612–614 (2002).
6. J. Masson, R. St-Gelais, A. Poulin, and Y.-A. Peter, "Tunable fiber laser using a MEMS-based in plane Fabry-Pérot filter," IEEE J. Quantum Electron. **46**, 9 (2010).
7. X. Wang, T. Liu, V. R. de Almeida, and R. R. Panepucci, "On-chip silicon photonic wavelength control of optical fiber lasers," Opt. Express **16**, 15671–15676 (2008).
8. T. J. Kippenberg, S. M. Spillane, D. K. Armani, and K. J. Vahala, "Fabrication and coupling to planar high-q silica disk microcavities," IEEE J. Quantum Electron. **83**, 797–799 (2003).
9. K. J. Vahala, "Optical microcavities," Nature **424**, 839–846 (2003).
10. S. Noda, A. Chutinan, and M. Imada, "Trapping and emission of photons by a single defect in a photonic bandgap structure," Nature **407**, 608–610 (2000).
11. S. Y. Lin, J. G. Fleming, D. L. Hetherington, B. K. Smith, R. Biswas, K. M. Ho, M. M. Sigalas, W. Zubrzycki, S. R. Kurtz, and J. Bur, "A three-dimensional photonic crystal operating at infrared wavelengths," Nature **394**, 251–253 (1998).
12. M. Cai, O. Painter, and K. J. Vahala, "Observation of critical fiber taper to a silica-microsphere whispering-gallery mode system," Phys. Rev. Lett. **85**, 74–77 (2000).
13. B. Little, S. Chu, H. Haus, J. Foresi, and J.-P. Laine, "Microring resonator channel dropping filters," J. Lightwave Technol. **15**, 998–1005 (1997).

#130093 - $15.00 USD Received 17 Jun 2010; revised 9 Jul 2010; accepted 12 Jul 2010; published 23 Jul 2010

14. M. Beaugeois, B. Pinchemel, M. Bouazaoui, M. Lesecq, S. Maricot, and J. P. Vilcot, “All-optical tunability of ingaasp/inp microdisk resonator by infrared light irradiation,” Opt. Lett. **32**, 35–37 (2007).
15. A. Zhang, H. Liu, M. Demokan, and H. Tam, “Stable and broad bandwidth multiwavelength fiber ring laser incorporating a highly nonlinear photonic crystal fiber,” IEEE Photon. Technol. Lett. **17**, 2535–2537 (2005).
16. D. Armani, B. Min, A. Martin, and K. J. Vahala, “Electrical thermo-optic tuning of ultrahigh-Q microtoroid resonators,” Appl. Phys. Lett. **85**, 5439–5441 (2004).

---

1. Introduction

Erbium doped fiber is widely used in the telecommunication for signal amplification. It can also be used as a wideband light source in the form of erbium doped fiber lasers (EDFL). These lasers offer a wide range of applications varying from telecommunication to fiber optic sensing [1, 2]. Multi-wavelength EDFLs are needed for multi-channel applications such as wavelength division multiplexing (WDM) communication and parallel sensing systems. Many periodic multi-frequency lasers have previously been demonstrated by various groups [1, 3, 4]. Non-periodic multi-wavelength systems exhibiting multi-wavelength emission with no relation between the emitting channels have been barely investigated to date. In these systems, each laser emission channel is independent from the others so that the channel spacings are fully customizable. This is usually achieved using multiple independent filters such as fiber Bragg gratings [5]. We propose here a single integrated filter made of several independent components capable of non-periodic filtering. This new type of integrated filter can be used as a key element for simple non-periodic multi-wavelength lasers that can replace tunable lasers in many sensing applications [2].

To select the emission wavelength of an erbium doped fiber laser, one needs to control the gain profile inside the cavity of the laser. This is achieved by filtering the signal, thus inducing high loss at the undesired wavelengths, preventing them from reaching the lasing threshold. Such filters have been reported using integrated optics [6, 7]. Integrated optic filters offer many advantages such as low-cost/high volume production, small volumes, tunability and good optical performance, such as low optical loss and high confinement leading to high quality factors. Silica microdisk cavities offer many advantages needed in the elaboration of configurable high performance spectral filters. Silica cavities are easily fabricated with conventional microfabrication processes, offer low absorption loss and great compatibility with optical fibers [8]. In addition the microdisk geometry confines light in the form of high quality factor whispering gallery modes [8], which gives rise to narrow filtering linewidths. These very narrow linewidths could potentially provide extremely stable laser emission exceeding even the performances of Bragg grating based fiber lasers.

In this paper we demonstrate such microdisk filters to control the spectral emission of an erbium doped fiber laser. Both single and multiple wavelength lasers were produced. Periodic and non-periodic multi-frequency lasers can be designed with various microdisk filters, such as single cavity filters with customizable periodic resonances and multiple independent cavity filters with non-periodic resonances.

2. Silica Disk Optical Microcavities

Optical microcavities are structures that can trap light in a confined area for a specific amount of time. They can have various geometries and materials [9]. Fabry-Perot are one dimentional cavities which can be made by combining two optical Bragg reflectors [6]. Photonic crystals cavities achieve confinement in two and three dimensions [10,11]. Another strategy is to confine light using the total internal reflections caused by a step index interface. Cavities using total internal reflection confinement, such as microsphere [12], microdisk [8] and microring [13] resonators have been demonstrated with very good properties. In addition, different materials

#130093 - $15.00 USD Received 17 Jun 2010; revised 9 Jul 2010; accepted 12 Jul 2010; published 23 Jul 2010

can be used to fabricate these microdisk cavities, such as silicon [13], silica [8] or various active materials [14].

In this work, we use silica microdisk resonators. To fabricate these microdisks we start with an oxidized silicon wafer (Fig. 1a) with 2 μm of SiO_2. Next, using conventional UV lithography (Fig. 1b), we pattern microdisks into the resist. We then create the resonators by anisotropic etching of the SiO_2 layer using reactive ion etching (RIE) (Fig. 1c). Finally, to prevent mode leakage into the substrate, we isotropically etch the silicon under the cavity's edge using an inductively coupled plasma (ICP) of SF_6 (Fig. 1d). Figure 1 shows fabricated microdisk cavities in both single (Fig. 1e) and multi (Fig. 1f) cavity pattern.

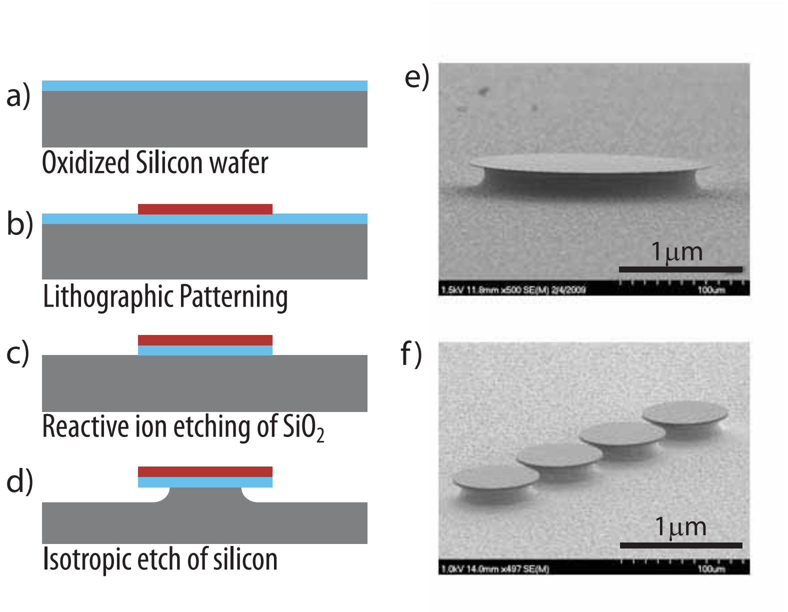

Fig. 1. a) to d) Schematic of the microfabrication process. e) SEM photograph of a single cavity filter. f) SEM photograph of a multi-cavity filter composed of four resonators with different diameters.

Light is guided in the microdisk by total internal reflection due to the step in refractive index between the cavities (silica) and it's surrounding environment. Resonant modes are determined by the circular geometry of the microdisk according to the Eigen modes of the cavity. The whispering gallery modes (WGM) offer extremely high confinement at the periphery of the cavity, which results in very high quality factors. These extremely high quality factors allow very narrow bandwidth optical filters.

3. Spectral Filters Using Optical Microdisk Cavities

By using evanescent coupling between silica microdisks and a dielectric waveguide, it is possible to generate a variety of spectral filters. In these experiments, we used tapered optical fibers to achieve evanescent coupling, as described in [8] and [12]. The very high quality factor of silica microdisk cavities allows a very selective filtering of resonant wavelengths. The inset of Fig. 2c) shows a rejection filter with a full width at half maximum (FWHM) of 46 pm, which corresponds to a quality factor of 3.3×10^4.

By coupling a single optical microdisk with a single tapered optical fiber, as shown in Fig.

#130093 - $15.00 USD Received 17 Jun 2010; revised 9 Jul 2010; accepted 12 Jul 2010; published 23 Jul 2010

2a), we get a drop filter (Fig. 2c plain curve). The evanescent field from the fiber overlaps with one or more of the cavity modes, enabling a small amount of the input signal to be coupled into the cavity. Once coupled into the cavity, only resonant wavelengths build up and finally recouple into the original tapered fiber. The reinjected signal interfere destructively and attenuate transmission for the cavity's resonant wavelengths. Using a broadband signal (input 1), it is possible to reach very high attenuation at the resonant wavelengths of the cavity, as shown in Fig. 2c). These measurements have been obtained using a tunable laser source and optical detector (Agilent 81600B and 81634B) with a spectral resolution of 4pm over a span of 14 nm. The 0 dB transmission reference was obtained by measuring the transmission through the unperturbed fiber taper prior to evanescent coupling. The optical coupling technique consists in bringing the optical fiber taper in physical contact with the microcavity. This does not ensure optimal coupling but does provide reasonable repeatability.

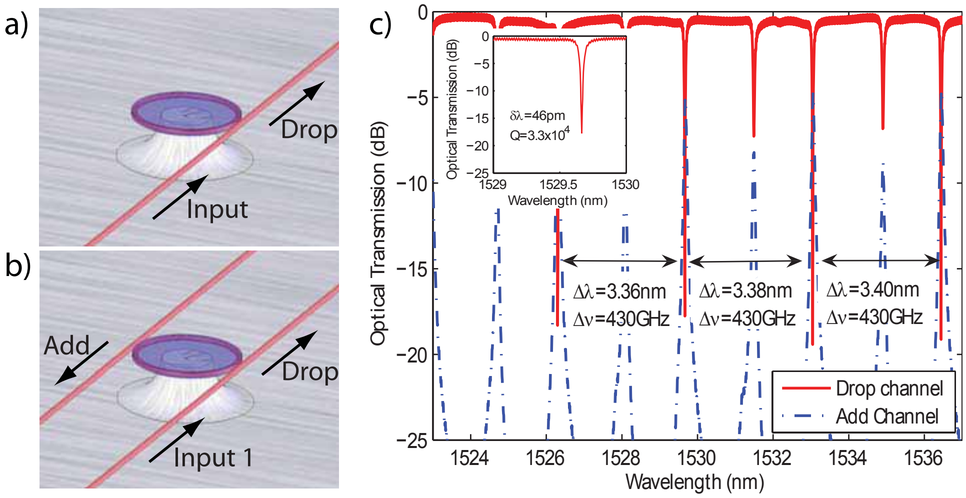

Fig. 2. Optical microdisk (a) Drop and (b) Add/Drop filters. (c) Spectral transmission for Add and Drop periodic channels. Inset shows linewidth and quality factor of a resonance.

It is also possible to make very narrow pass filter. By adding a second tapered fiber to the previous filter, the optical power traped inside the cavity can then be extracted (Fig. 2b). Figure 2c) shows transmission spectra of both a drop and a pass filter made from the same cavity. In this configuration, the reference level was obtained by bypassing both optical tapers with an optical patch cable. This will include the optical loss due to the optical tapers into the transmission measurement. The presented single cavity filters demonstrate insertion losses in the order of -5dB, whereas multicavity filters, such as the ones which will be discussed later, demonstrate higher insertion losses (up to -14dB for a four cavity filter) since the number of cavities increases. The loss is mainly due to the coupling scheme bringing the optical fiber taper in physical contact with the microcavity.

By using both inputs, this filter can be used as an add/drop filter. In this configuration a single channel, corresponding to a resonant wavelength, can be transferred from one optical fiber to another while leaving the other wavelengths untouched.

Microdisk filters can be designed to operate at any wavelength and with a wide range of free spectral ranges by changing the diameter of the cavity, as demonstrated in Eq. (1), Eq. (2) and

#130093 - $15.00 USD Received 17 Jun 2010; revised 9 Jul 2010; accepted 12 Jul 2010; published 23 Jul 2010

Eq. (3).

$$\lambda = \frac{2\pi R n_{eff}}{m}, \tag{1}$$

$$FSR(\lambda) \approx \frac{\lambda^2}{2\pi R n_{eff}}, \tag{2}$$

$$FSR(\nu) = \frac{c}{2\pi R n_{eff}}, \tag{3}$$

where λ and ν are the resonant wavelength and frequency respectively, R the radius of the WGM, n_{eff} the effective refractive index, c the speed of light and m is the azimuthal number of the mode (represents the eigenmode's order). Eq. (1) is directly related to the optical path length inside the cavity, and Eq. (2) and Eq. (3) can be derived from Eq. (1) by using two consecutive azimuthal modes (m and m+1).

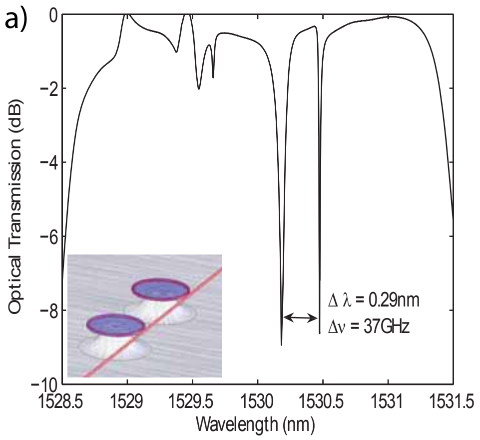

Fig. 3. Multi-cavity filters and spectra. a) Two cavity filter with 200 μm diameter and a variation of about 40 nm to obtain a 0.29 nm spacing between the two resonances. b) Four cavity filter with 70 μm diameter and a variation of about 50 nm to obtain about 1 nm spacing between each resonance (uneven because of fabrication deviations).

Single cavity devices can be used to create single wavelength filters by decreasing the diameter of the disk to reach an FSR larger than the useful spectral band of the application. Contrarily, large diameters can be used to create periodic multi-frequency filters as previously seen in Fig. 2c). The FSR of a cavity is a function of wavelength squared [see Eq. (2)], whereas in the frequency domain the FSR is not wavelength dependant [see Eq. (3)]. This frequency periodicity is very useful in many multi-wavelength applications such as WDM channel spacing. These filters can also be fabricated to operate in a non periodic multi-frequency mode by using multiple cavities with different diameters. Figure 3 presents two examples of multiple cavity filters. The first filter, Fig. 3a), uses two almost identical cavities to produce a two-wavelength filter with very small spacing (0.29nm) between the resonances (diameter variation of about 40 nm). The second filter, Fig. 3a), was designed to be a four wavelength periodic filter with 1 nm spacing between each resonance. Fabrication deviations (at the patterning step) have produced a fully non-periodic multy-wavelength filter.

Silica microdisk cavities can thus be used to generate customizable spectral filters. The extremely high quality factor of step index optical microdisk cavities allows for very narrow

Received 17 Jun 2010; revised 9 Jul 2010; accepted 12 Jul 2010; published 23 Jul 2010

spectral filtering. Furthermore, the microfabrication techniques used to create these cavities facilitates the design and allows mass fabrication of multi-cavity filter geometries.

4. Erbium doped fiber laser controlled by microdisk cavity filters

The emission spectrum of an erbium doped fiber laser can be controlled by inserting a spectral filter into the cavity of the laser. Only high transmission wavelengths will achieve laser threshold. In our case, this corresponds to the microdisk's resonant wavelengths. Figure 4a) presents a schematic of the fiber laser used in these experiments. The setup consists of a ring cavity with a WDM coupler to inject the 980nm pump light, and a tap coupler to extract the output power of the laser. A very low output tap percentage (1%) was used to minimize cavity loss and maximize lasing. The erbium doped fiber was kept short (2m) to minimize short wavelength absorption and no gain flattening techniques were applied thus creating a narrow (≈10 nm) high gain region around 1530 nm. An optical isolator forces a contrapropogation of laser light relative to the pump propogation. A polarization controller is used to select a specific resonance mode with a specific state of polarization. Finally, a microdisk pass filter is placed between the output tap and the isolator to generate spectral selectivity of the laser emission.

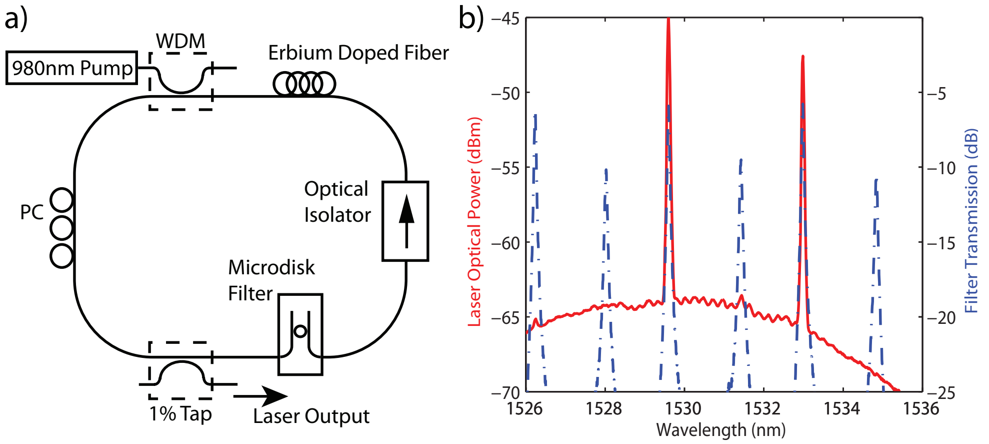

Fig. 4. a) Schematic of erbium doped fiber laser with microdisk filter. b) Spectra of laser emission (plain line) and filter transmission (dashed line), obtained using a single cavity filter with a diameter of 150 μm and a periodic FSR of 430 GHz. The laser emission is measured using an optical spectrum analyzer with a resolution of 0.02 nm.

The spectral filter selects specific wavelengths from erbium spontaneous emission spectrum before reinjecting them into the gain medium. Excited by the 980 nm pump, erbium emits in a very wide spectrum. If this broad spectrum is allowed to go through a few cavity round trips, lasing will occur at various wavelengths, for which gain is sufficient. By filtering the spontaneous emission at every round trip, only resonant wavelengths of the microcavity are allowed to be reinjected into the erbium doped fiber and amplified by stimulated emission, resulting in a controlled emission at the resonant wavelengths of the filter. The very narrow linewidth of these filters significantly reduces the influence of noise generated inside the gain medium providing to the laser a very good spectral stability. Figure 4b) shows the laser emission (plain line) and the filter transmission spectrum (dashed line). The filter used had two excited radial modes, both with a FSR of around 3.5 nm. The 4dB difference in transmission between the main and secondary modes prevents the secondary modes from lasing. The width of the high gain region (around 1527 nm to 1534 nm for this laser configuration) determines the number of resonances that will lase. In this case, two main modes have enough gain to generate lasing. A third resonant mode is seen to be very close to the high gain region but still slightly below the lasing condition. By using a longer erbium doped fiber, thus increasing the absorbed pump power, and using gain flattening techniques, we could obtain a periodic laser emission over the entire erbium gain region, according to the resonant frequencies of the filter.

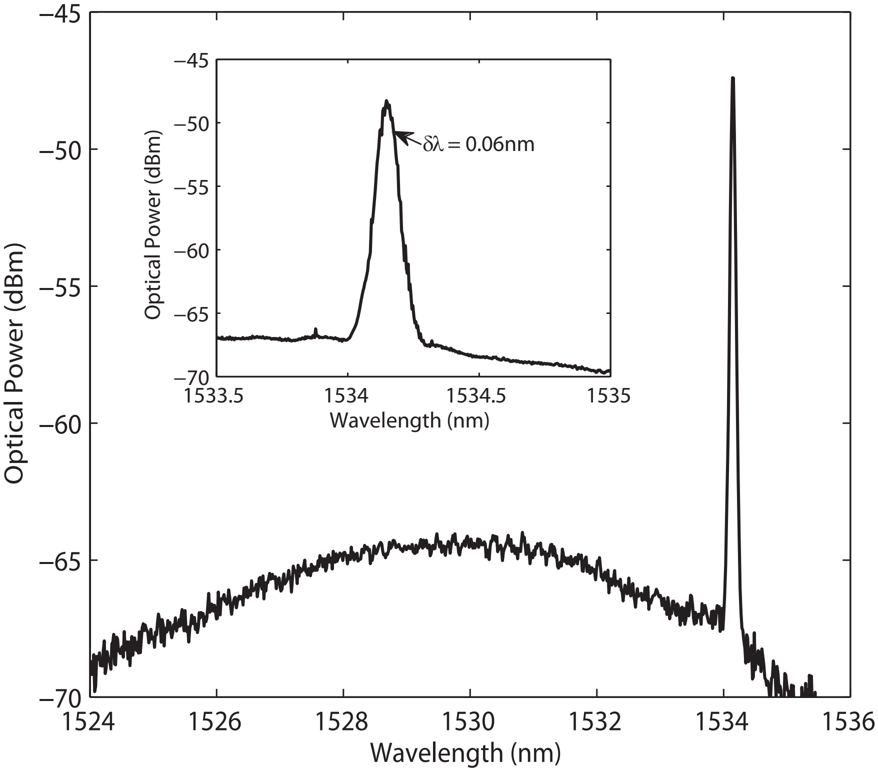

Fig. 5. Single mode laser emission using single 40 μm diameter cavity filter. Inset shows a measured FWHM of 0.06nm.

Figure 5 shows a single mode laser spectrum obtained using a single 40 μm diameter cavity filter. The size of the cavity insures that the FSR is large enough so that no other resonant wavelengths are present in the high gain region. The inset shows the measured bandwidth (FWHM) of the laser emission to be smaller than 0.06 nm (limited by the resolution of the optical spectrum analyzer), which is comparable to previous works [1, 15].

Both single and multi-wavelength fiber lasers have been demonstrated, using various filter types. Figure 6 presents other examples of controlled emission. The first spectrum (Fig. 6a) shows a multi-wavelength laser which was designed by using a filter made of two cavities with slightly different diameters (variation of $\approx$ 40 nm). We can observe two emission peaks with a spacing of 0.28 nm. Each emission peak corresponds to a single resonant wavelength from each of the cavities. The second spectrum (Fig. 6b) presents a non periodic multi-wavelength laser using a four cavity filter. The filter is of irregular channel spacings of approximately one nanometer. It demonstrates the possibility of generating non periodic multi-wavelength EDFLs using a filter with multiple microdisks.

#130093 - $15.00 USD Received 17 Jun 2010; revised 9 Jul 2010; accepted 12 Jul 2010; published 23 Jul 2010

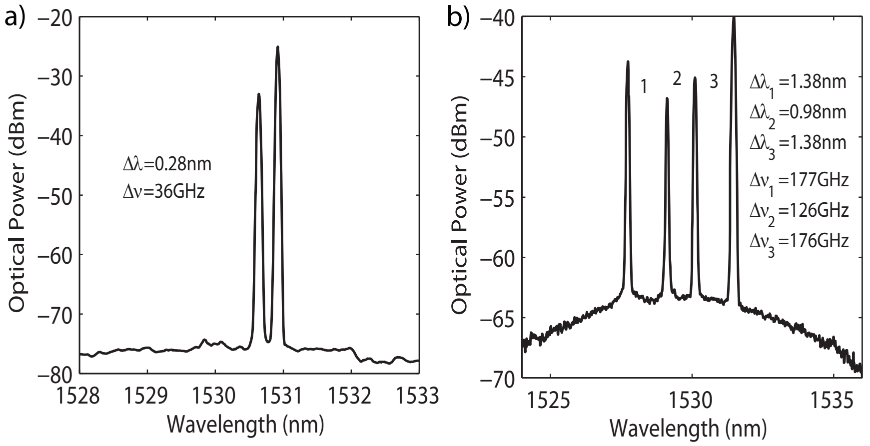

Fig. 6. Emission spectra of fiber lasers using multi-microdisk filters. a)Two-wavelength using a two cavity filter, b)Non-periodic multi-wavelength using a four cavity filter

It is thus possible, using these filters, to design erbium doped fiber laser with tailored emission spectra. It is to be noted that the precision with which we can design these filters is highly dependent on the fabrication tolerances. Very precise spectral specification can lead to the use of expensive high accuracy photolithographic masks and processes. These fabrication restriction can also be compensated by actively tuning the filter as demonstrated in references [7, 16].

5. Conclusion

In this paper we demonstrated the use of silica microdisk resonator filters to control the spectral emission of an erbium doped fiber laser. Both single and multiple wavelength lasers were realized. The combination of multiple silica microdisk cavities in a single filter allows the design of non-periodic multi-wavelength EDFLs. Emission spacing as low as 0.28 nm and non-periodic four wavelength lasers have been achieved using multi-cavity filters. This novel technique enabling the control of the emission of fiber lasers can lead to new low-cost and customizable multi-wavelength light sources. The new source could find many applications in telecommunication and parallel optical sensing such as infrared spectroscopy. Slow tunable lasers could be replaced in specific applications by custom multi-wavelength lasers able to probe a sample with predefined wavelengths in a single measurement.

Acknowledgements

The authors would like to thank the Fibre Optics Laboratory directed by Profs. Lacroix and Godbout at École Polytechnique de Montréal for providing access to their tapered fiber fabrication setup. This work was supported by the Fonds Québécois de la Recherche sur la Nature et les Technologies, Equip Grant 119043.