

# Widely tunable erbium-doped fiber laser based on multimode interference effect

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**Abstract:** A widely tunable erbium-doped all-fiber laser has been demonstrated. The tunable mechanism is based on a novel tunable filter using multimode interference effects (MMI). The tunable MMI filter was applied to fabricate a tunable erbium-doped fiber laser via a standard ring cavity. A tuning range of 60 nm was obtained, ranging from 1549 nm to 1609 nm, with a signal to noise ratio of 40 dB. The tunable MMI filter mechanism is very simple and inexpensive, but also quite efficient as a wavelength tunable filter.

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## 1. Introduction

Tunable fiber lasers are attractive because their emission wavelength can be systematically tuned within a certain spectral range. This allows the use of a single source instead of several sources, which is convenient and cost-effective for many applications in a range of disciplines, including telecomm, material processing, microscopy, medicine and imaging. Many of the techniques which have been applied to implement a wide tuning mechanism in the laser cavity, are mainly oriented toward telecomm applications. Techniques using bulk grating [1], fiber Bragg grating [2–4], SOA fiber laser based on Sagnac loop mirror via polarization tuning [5], and Fabry Perot cavity [6] have proven to be excellent tunable telecomm sources. Unfortunately, these techniques are either very expensive or require very complex setups in which alignment issues could make the laser highly sensitive to environmental conditions.

Devices based on multimode interference (MMI) effects have recently attracted significant interest for a range of applications. The vast majority of MMI applications have been related to integrated optics such as MMI optical coupler devices [7,8], MMI splitters for sensing applications [9], and MMI switches [10,11]. The development of fiber based MMI devices is relatively new, and few devices have been demonstrated so far. A common feature of the fiber based MMI devices is that they rely on the wavelength dependence exhibited by the self-imaging effect. Therefore, the fiber based MMI works as a band-pass filter and thus can be applied for different applications. They have been used as displacement sensors [12], band-pass filters [13], as well as their use to provide single-transverse-mode laser emission from multimode active fibers [14]. The only drawback of the fiber based MMI filter is that the peak wavelength response of the filter is usually fixed. The first attempt to develop a tunable fiber based MMI filter was to incorporate a broadband mirror in front of one of the multimode fiber (MMF) facets while the other is fusion spliced to the single mode fiber (SMF) input. By moving the mirror back and forth, the effective length of the MMF is changed and wavelength tuning is achieved. Using this effect a tunable ytterbium-doped fiber laser was developed with a tuning range of 8 nm [15]. However, the alignment of the MMF facet perpendicular to the broadband mirror was very difficult. The tuning mechanism was improved using a gold-coated fiber facet as the mirror and an integrated SU-8 fiber gripper for automatic fiber alignment [16]. Although this modification enhanced the tunable range up to 12.24 nm, the tuning range was now limited by the Fabry-Perot resonances created by the cavity formed by the MMF facet and mirror.

In this paper, we report a widely tunable erbium-doped fiber laser based on the MMI effects. The tunable mechanism is based on a fused silica ferrule filled with a refractive index matching fluid. When the ends of the SMF and MMF are inserted in the ferrule, their separation can be easily changed in order to tune the MMI peak wavelength. The refractive index fluid creates a liquid multimode waveguide that not only allow us to achieve larger separations (wider tuning range), but also eliminates the issues related to Fabry-Perot resonances. The tuning mechanism was incorporated within an erbium-doped ring cavity laser and we were able to achieve a tuning range of 60 nm, going from 1549 nm to 1609 nm, with a signal to noise ratio (SNR) better than 40 dB. It is worth mentioning that this device provided an acceptable fiber alignment and a highly stable system since the fibers are held within the

ferrule. Additionally the device is quite simple and relatively inexpensive when compared with other tuning techniques.

## 2. Operation of the Tunable MMI filter

A typical MMI filter consists of a MMF spliced between two SMF. The MMI effect takes place when light is coupled through the SMF and excites all the modes supported by the MMF. Single images of the SMF input signal will appear along the MMF at periodical intervals along its axis due to the interference between the modes as they propagate along the MMF. According to MMI theory the peak wavelength of a MMI device is given as [7,17]

$$\lambda_0 = p \frac{n_{MMF} D_{MMF}^2}{L} \quad \text{with } p = 0, 1, 2, \dots \quad (1)$$

where  $n_{MMF}$  corresponds to the refractive index,  $D_{MMF}$  the diameter of the MMF core,  $L$  being the length of the MMF, and  $p$  the self-image number. As shown in Eq. (1), the peak wavelength response of the MMI filter can be selected by simply changing the length of the MMF. Therefore, in order to fabricate a tunable MMI filter, we need to design a mechanism to effectively change the length of the MMF in real time. An additional advantage when changing the length of the MMF for tuning is that we obtain a linear wavelength response of the MMI device which is important for some applications.

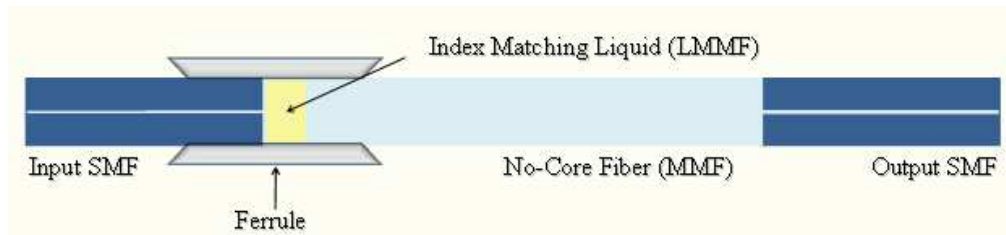


Fig. 1. Schematic of the novel tunable MMI filter. The MMI filter is formed by the MMF (LMMF & No-core Fiber) between the two single mode fibers.

A schematic of our proposed tunable MMI filter is shown in Fig. 1. The operational principle of the device is quite simple. The main idea is to form a multimode waveguide whose length could be changed at will. Therefore, when liquid is inserted in the fused silica ferrule, a liquid multimode fiber (LMMF) will be formed if the refractive index of the liquid is higher than that of the ferrule. We can now open one of the SMF-MMF splices of the MMI filter and insert the fibers within the ferrule as shown in Fig. 1. Therefore, any gap between the SMF and MMF is now a LMMF, and this effectively increases the length of the MMF. By changing the separation between the SMF and MMF, we control the effective MMF length and thus wavelength tuning should be achieved.

The fused silica ferrule has a length of 15 mm, and an inner and outer diameter of 127  $\mu\text{m}$  and 1700  $\mu\text{m}$  respectively (Polymicro Technologies). The ends of the ferrule are flared to facilitate the fiber insertion into the ferrule. Regarding the MMF fiber, it is important to mention that any kind of MMF can be used to observe MMI effects. However, the MMF used in our experiments is a specialty fiber known as no-core fiber. The no-core fiber is a MMF having a diameter of 125  $\mu\text{m}$  and refractive index of 1.463 with air as its cladding. This fiber was used since having a bigger  $\Delta n$  difference between core and cladding provides a narrow MMI filter bandwidth as well as a higher contrast [9]. The length of the no-core fiber was 58.93 mm, which corresponds to the fourth self-image ( $p = 4$  in Eq. (1)). This image number is selected since, compared to the other images ( $p = 1, 2,$  and  $3$ ), this image exhibits the lowest insertion loss and also exhibits a narrower wavelength bandwidth. Given the ferrule and no-core fiber dimensions, the fibers are reasonably aligned in the transverse direction after their insertion into the ferrule. This also allowed us to move the fibers very smoothly along the propagation direction in order to tune the MMI filter.

The index matching liquids to form the LMMF were provided by Cargille Labs. In principle, the refractive index of the liquid has to be higher than that of the ferrule and lower than the no-core fiber in order to guide light and prevent additional losses respectively. Nevertheless, we decided to test different refractive indexes and study their influence on the MMI spectral response. Measurements were taken by first filling the ferrule with the liquid, and then inserting the SMF and MMF fibers in the ferrule until the facets made contact with each other. This region was placed at the center of the ferrule for all the measurements. An Agilent tunable laser was used as the input source. After passing through the MMI filter the transmitted light was measured using a photo-detector. Since the MMF length was fixed, the peak wavelength remained fixed regardless of the refractive index of the liquid. However, there was a noticeable change on the MMI filter bandwidth as the refractive index of the liquid was changed as shown in Fig. 2.

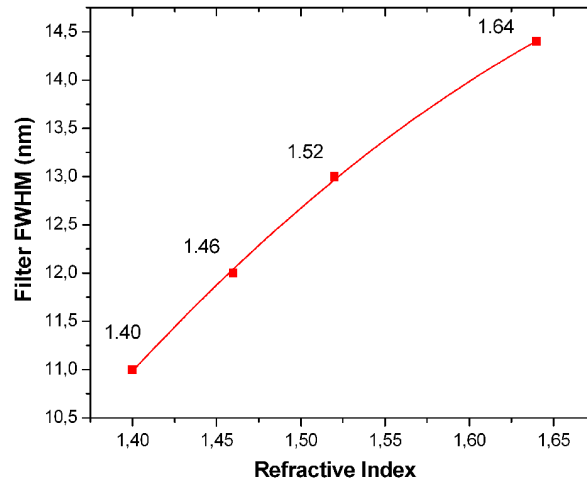


Fig. 2. MMI Filter bandwidth at FWHM as a function of different refractive index matching liquids.

The results show that the bandwidth of the filter is narrowed as the refractive index of the liquid is reduced. We could also notice that at higher refractive index values the losses were slightly higher, which can be correlated with light leaking out of the no-core fiber. Although the liquid with the lowest refractive index should be ideal, we have limitations related to the ferrule and no-core fiber. Therefore, since the refractive index of the ferrule is 1.444 and the no-core fiber is 1.463, we selected a refractive index matching liquid of 1.45 for all the experiments.

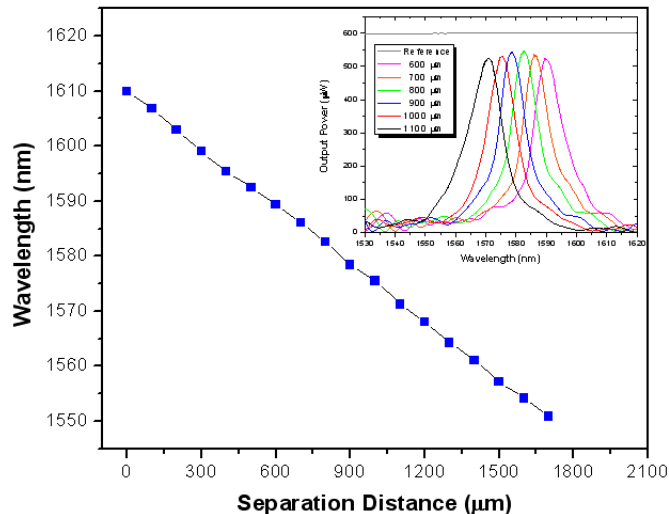


Fig. 3. Peak wavelength response of the MMI filter as a function of the separation between fibers in the ferrule. Inset: MMI filter spectral response for different fiber gaps.

The MMI filter performance was then characterized by varying the separation between the SMF and MMF in small steps, and measuring its spectral response at each step. However, we observed that as the separation between the fiber facets was increased, the insertion losses were also increased. We believe that this is related to the small diameter mismatch between the diameter of the silica ferrule ( $127\mu\text{m}$ ) and that of the no-core fiber ( $125\mu\text{m}$ ) and also for the ferrule imperfections. Therefore, as the fibers move away from each other there might be some tilting between the facets which can deteriorate the coupling of the self-image to the output SMF. In order to minimize this loss, we first determined the tuning range (i.e. maximum gap between fiber facets) and maximized the transmitted intensity at the center of the tuning range by carefully moving the remaining fibers out of the ferrule in the transverse direction. We can then move back and forth from this position in order to tune the MMI filter. For clarity, the optical power spectral response of the filter for six different separations is shown in Fig. 3 (inset) for a constant input power. The highest loss at the end of the widest tuning range is 0.24 dB, which added to the 0.4 dB loss at the center of the tuning range makes a total insertion loss of 0.64 dB. After alignment of the MMI filter, a total tuning range of 60 nm can be achieved, as shown in Fig. 3. This tuning range corresponds to a separation between the fibers of 1.8 mm. Beyond this range, the insertion losses will increase very rapidly. We believe that this could be related to the non-uniformity of the capillary inner diameter since a shift or tilt on the fiber facet affects the self-image output coupling. Therefore, a more uniform capillary with a diameter closer to the diameter of the MMF should in principle allow us to increase our tuning range.

### 3. Tunable Erbium-doped Fiber Laser

The tunable erbium-doped fiber laser (EDFL) was fabricated using a standard ring cavity configuration which is shown in Fig. 4. A 980 nm laser diode with 150mW of maximum output power from Lucent Technologies was used as the pump source. The pump was coupled into the cavity using a 980/1550 wavelength division multiplexer (WDM). The WDM (port 3) was fusion-spliced with a 2.85 m long L-band Erbium-doped fiber (EDF) having a 0.25 NA and a concentration of 3000 ppm. The other cleaved end of the EDF was placed into the ferrule filled with index matching liquid with RI of 1.45. The EDF works now as the input SMF in out MMI filter. At the other end of the capillary, the no-core fiber spliced to the output SMF is inserted into the ferrule to complete the MMI filter. The output SMF is then spliced to a 90/10 coupler to monitor the laser. The 10% output was connected to an optical

spectrum analyzer (OSA) while the 90% was spliced to an optical isolator. The ring cavity is then closed by connecting the isolator output to the WDM (port 2).

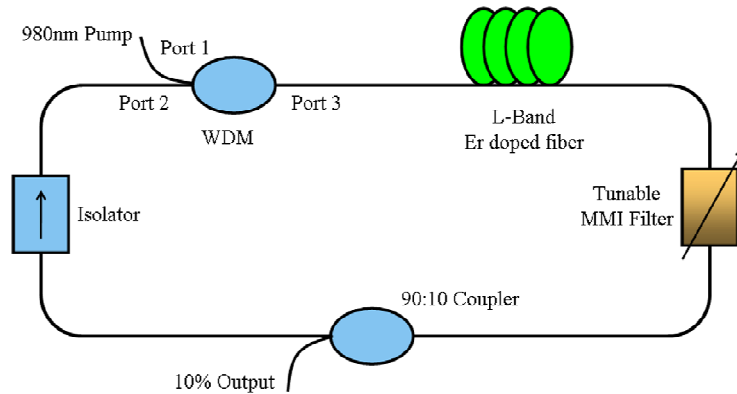


Fig. 4. Schematic layout of the tunable erbium-doped fiber laser based on the MMI.

The laser was operated at maximum pump power, and the tunable MMI filter was adjusted for minimum insertion losses as previously described. The maximum laser output power obtained was roughly about 1 mW. Wavelength tuning was achieved by varying the separation between fibers in 100  $\mu\text{m}$  steps, and the lasing spectra was acquired with the OSA at each step. The optical spectrum at different fiber separations is shown in Fig. 5. It is clear from the graph that the laser exhibits a total tuning range of 60 nm covering a wavelength range from 1549 nm to 1609 nm. We should also highlight that the laser wavelength can be adjusted continuously within the tunable range. The measured laser linewidth was 0.4 nm, and the signal-to-noise ratio (SNR) is about 40 dB.

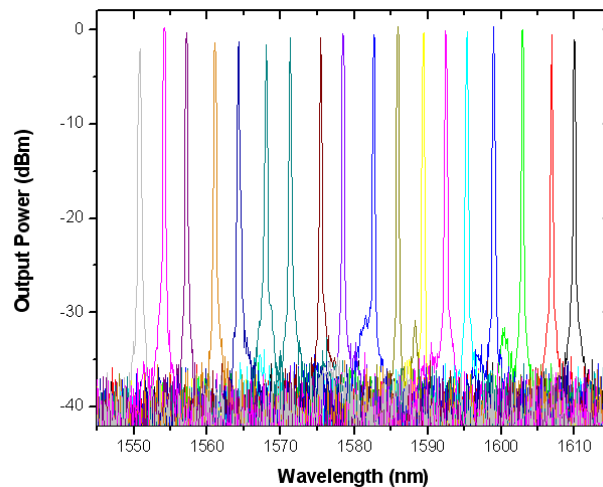


Fig. 5. Experimental tuning results, output power versus wavelengths: 60nm tuning with more than 40 dB contrast.

Our results demonstrated the advantage of the MMI filter for developing tunable lasers and could also be used for other applications. The key advantages of the MMI filter is that is quite simple to fabricate and also inexpensive when compared to other tuning mechanisms. In addition, since the peak wavelength response of the laser can be changed by using a MMF with a different length, our MMI filter can be easily applied to any kind of rare-earth doped fiber laser in order to provide different wavelength ranges. The filter could also be applied for high power applications, such as those based on ytterbium doped fibers, since the refractive

index matching liquids have boiling points of at least 100 °C or implemented together with a master oscillator power amplifier (MOPA) configuration.

#### **4. Conclusions**

A widely tunable erbium-doped fiber laser was demonstrated. The tuning mechanism relies on a novel tunable MMI filter that provides a wide tuning range while maintaining a very simple and cost effective device. We obtained a tuning range of 60 nm with a laser line-width of 0.4 nm. The SNR was roughly 40 dB and the optical output power was at least 1mW. Operating the MMI filter at higher powers should not be an issue, but this was not investigated in this work. The tunable laser is remarkably inexpensive and uniquely portable due the simplicity of the constituent elements. This tunable fiber can be applied in technologies like optical communication, specifically in DWDM and CWDM, and also in medicine, for example, in skin treatments.

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