Tunable multimode-interference bandpass fiber filter

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We report on a wavelength-tunable filter based on multimode interference (MMI) effects. A typical MMI filter consists of a multimode fiber (MMF) spliced between two single-mode fibers (SMF). The peak wavelength response of the filter exhibits a linear dependence when the length of the MMF is modified. Therefore a capillary tube filled with refractive-index-matching liquid is used to effectively increase the length of the MMF, and thus wavelength tuning is achieved. Using this filter a ring-based tunable erbium-doped fiber laser is demonstrated with a tunability of 30 nm, covering the full C-band. © 2010 Optical Society of America

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Tunable filters are key components for a variety of applications, in particular for telecomunications systems. The tunable wavelength range from a tunable laser, for example, relies entirely on the tunable range provided by the tunable filter being used. According to the technology used to fabricate the filter, we can classify the filters as externally coupled filters, such as bulk gratings and volume Bragg gratings [1–3], or all-fiber based filters such as fiber Bragg gratings (FBG), long period gratings (LPG), in-line Fabry–Perot (FP) filters, and filters based on specialty fibers [4–7]. In the case of externally coupled filters, wide wavelength tuning ranges have been achieved, but the arrangement is typically bulky as a result of the external gratings. There is also a major issue concerning alignment and stability of the system itself, which makes it sensitive to external disturbances. A solution to this problem is to make an all-fiber tunable laser system. Therefore, there have been different approaches in order to achieve an all-fiber widely tunable filter. FBGs with tuning ranges wider than 40 nm are feasible, but they rely on stretching or compression, which makes them unreliable for long-term operation. In the case of LPGs, a wider tuning range is feasible, but we still have to write the grating in the fiber, which increases fabrication costs. In-line FP filters are commercially available with good tuning range but they are rather expensive devices. Recently, we demonstrated the use of multimode interference (MMI) effects in multimode fibers (MMF) as a simple tunable mechanism [8,9]. The advantage of such filters is that they require only the splicing of a section of MMF between two single-mode fibers. However, the maximum tuning wavelength range has been limited to only 12 nm. This limitation is not due to the MMI filter itself but rather from other effects arising from the way the filter was implemented.

In this Letter we report a wavelength-tunable MMI filter. The tuning mechanism relies on a capillary tube filled with a high refractive index liquid to effectively increase the length of the MMF. According to the MMI theory, when the MMF length is modified its peak wavelength response is also modified, and thus wavelength tuning is achieved. Using this filter a ring-based tunable erbium-doped fiber laser (EDFL) is demonstrated with a tunability of 30 nm, covering the full C-band.

The operation of the MMI filter can be explained as follows. The only requirement is a multimode waveguide that supports several modes ($\geqslant 3$), which is spliced between two SMFs. After the supported modes are excited by launching a field using the input SMF, the interference between the modes propagating along the MMF gives rise to the formation of self-images of the input field along the MMF. Therefore the length of the MMF has to be precisely cleaved in order to have a self-image right at the facet of the output SMF. The MMI effect has been previously studied and the length of the MMF can be calculated using

$$L = p\left(\frac{3L_\pi}{4}\right) \quad \text{with } p = 0,1,2, \ldots\ ., \tag{1}$$

where p corresponds to the self-image number and L_π is the beat length,

$$L_\pi \cong \frac{4 n_{\mathrm{MMF}} D^2{}_{\mathrm{MMF}}}{3\lambda_0}. \tag{2}$$

Here n_{MMF} and D_{MMF} correspond to the refractive index and the diameter of the MMF core, with λ_0 as the free-space wavelength. According to Eq. (1) self-images should be periodically formed along the MMF. However, since the fourth image exhibits minimum losses, the MMI filter was operated at the fourth image. In a typical MMI, the fibers are spliced and thus the wavelength response is fixed. To make this a tunable filter, we have to look at the wavelength dependence of the filter. By combining the MMI governing equations (1) and (2) and expressing the peak wavelength in terms of all the other parameters we obtain

$$\lambda_0 = p\left(\frac{n_{\mathrm{MMF}} D^2{}_{\mathrm{MMF}}}{L}\right) \quad \text{with } p = 0,1,2,\ldots\ldots \quad (3)$$

As shown in Eq. (3), in order to tune the peak wavelength response of the filter, we need to modify the refractive index, the length, or the diameter of the MMF. Therefore, as shown in Fig. 1, a tuning mechanism is proposed to effectively modify the MMF length. The key component is a fused-silica (n = 1.444) ferrule with an inner diameter of 127 μm and an outer diameter of 5 mm that facilitates its handling. When the ferrule is filled with a high-refractive-index liquid with n = 1.62 (Cargille Index Matching Liquid), a liquid multimode waveguide (MMW) is formed within the ferrule. The SMF and MMF can then be inserted in the ferrule, and when the separation between them is changed, the effective length of the MMF will be the sum of the real MMF length plus the liquid MMW segment. Therefore, if the effective length of the MMF is increased, according to Eq. (3), the wavelength response should be effectively tuned.

Our MMI device is made of two different MMFs. It was recently shown that having a bigger refractive index difference between core and cladding provides an MMI filter with narrower linewidth and better contrast [10]. The fiber that fulfills this requirement is known as No-Core fiber, which is basically a 125 μm diameter MMF with air as the cladding. Since we are using a liquid with a high refractive index, inserting the No-Core fiber directly into the ferrule could result in losses, since liquid accumulates in the end of the ferrule. Therefore a section of No-Core fiber whose length is calculated to have the third image at its facet was spliced to an SMF. Another section of 105/125 MMF, having the length to form one image, is then spliced to the end of the No-Core fiber. The combined length of both MMFs still forms the fourth image, but the 105/125 MMF has a cladding and thus should not be affected by the high-refractive-index liquid.

The tunable MMI filter was characterized by coupling light to the input SMF from an Agilent tunable laser, with a range from 1460 to 1580 nm. After passing through the MMI filter, light is measured at the output SMF using an InGaAs photodetector. The response of the tunable MMI filter is shown in Fig. 2(a). Shown here is the response of the filter at every 200 μm separation between the SMF and the 105/125 MMF. A tuning range of almost 30 nm was easily achieved with less than 0.4 dB insertion losses. We can also observe an additional loss as the filter is tuned. This effect is minimized by optimizing the filter at the center of the 30 nm tuning range, and the loss is kept to less than 0.2 dB. Beyond this range the filter response is quickly degraded, which is related to an increased angle of the fiber facet resulting from the different diameters between ferrule and MMF, and to the limited length of the ferrule. The peak wavelength response of the filter for every 100 μm separation is also shown in Fig. 2(b). As shown here, the tuning range should be enough to easily cover the C-band.

The filter was then used to build an all-fiber tunable laser using a standard ring laser cavity, as shown in Fig. 3. The ring was composed of 5-m-long erbium-doped fiber (EDF), a C-band optical isolator to keep the laser unidirectional, a 980/1550 nm

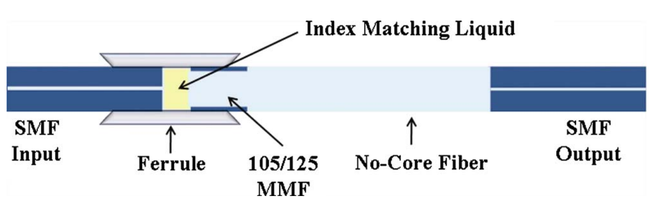

Fig. 1. (Color online) Schematic of the tuning mechanism for the tunable MMI fiber filter.

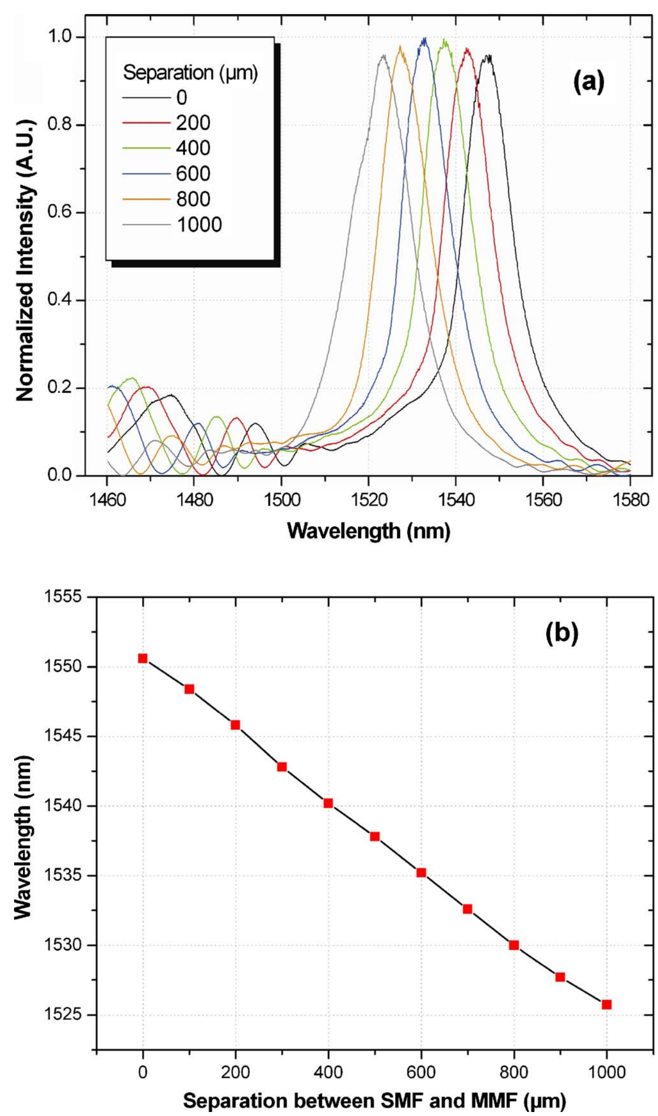

Fig. 2. (Color online) (a) Tuning response of the tunable MMI filter and (b) peak wavelength against separation between SMF and 105/125 MMF.

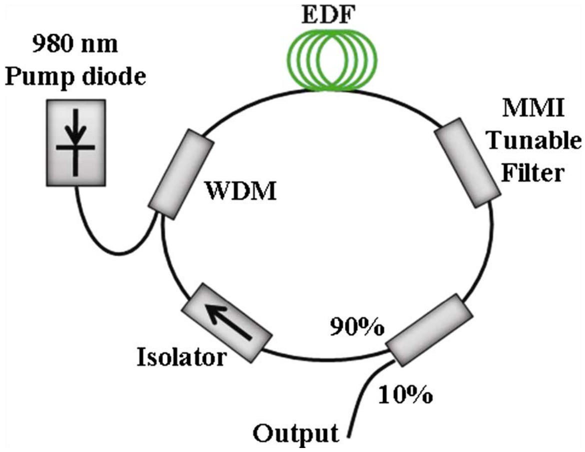

Fig. 3. (Color online) Experimental setup for the tunable MMI fiber laser.

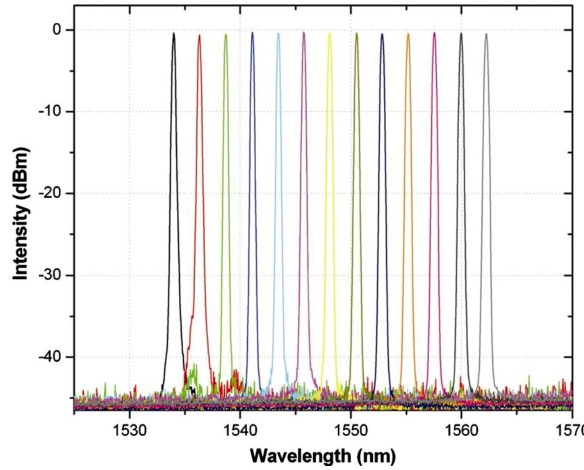

Fig. 4. (Color online) Superimposed spectral response of the tunable MMI fiber laser.

wavelength-division-multiplexing coupler to pump the EDF, a 10/90 coupler to monitor the tunability of the laser, and, of course, our tunable filter. The laser was pumped using a 980 nm wavelength laser diode with a power of 150 mW. At the 10% output coupler an optical spectrum analyzer (OSA) was used to monitor the spectral response of the tunable MMI laser. The tunability of the laser was characterized by first adjusting the filter to maximum transmission at the center of the tuning range, and then the SMF and 105/125 MMF were brought into contact. The EDF was pumped at maximum power, and laser spectral response was acquired using the OSA. Tuning was achieved by separating the fibers within the ferrule at small steps using a micrometer, and the spectrum is taken at every time. The superimposed spectrum of the tunable MMI laser exhibits a 30 nm tuning range as shown in Fig. 4. A side-mode suppression ratio (SMSR) of 45 dB was achieved, with a 3 dB bandwidth of 0.4 nm. The laser was operated at room temperature without any thermal control, and the peak wavelength was stable when monitored for several hours of operation. Power variation is also minimum, and given the resolution of the micrometer, continuous tuning can be easily achieved. We should also point out that, given the cost of the filter, expanding the tuning range is relatively simple and not expensive.

In summary, a tunable MMI bandpass filter with a 30 nm range and low insertion loss was demonstrated. The tuning mechanism relies in effectively increasing the length of the MMF, which is easily achieved using a simple capillary tube filled with a high refractive index liquid. Using this filter a ring-based tunable EDFL is demonstrated with a tunability of 30 nm covering the full C-band. This scheme results in a very simple and cost-effective tunable filter that can find applications in sensing and optical communications.

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