Wavelength tuning of fiber lasers using multimode interference effects

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Abstract: We report on a novel scheme to fabricate a simple, cheap, and compact tunable fiber laser. The tuning is realized by splicing a piece of single-mode fiber to one end of an active double-clad fiber, while the other end of the single-mode fiber is spliced to a 15 mm long section of 105/125 multimode fiber. The fluorescence signal entering into the multimode fiber will be reproduced as single images at periodic intervals along the propagation direction of the fiber. The length of the multimode fiber is chosen to be slightly shorter than the first re-imaging point, such that the signal coming out from the single mode fiber is obtained in free space, where a broadband mirror retroreflects the fluorescence signal. Since the position of the re-imaging point is wavelength dependent, different wavelengths will be imaged at different positions. Therefore, wavelength tuning is easily obtained by adjusting the distance between the broadband mirror and the multimode fiber facet end. Using this principle, the tunable fiber laser revealed a tunability of 8 nm, ranging from 1088-1097 nm, and an output power of 500 mW. The simplicity of the setup makes this a very cost-effective tunable fiber laser.

OCIS codes: (140, 3600) Lasers, tunable ; (060.2310) Fiber optics

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1. Introduction

Recently, considerable interest has been shown in the development of cladding pumped fiber lasers (CPFLs) because of their exceptional characteristics for practical applications. The pumping scheme constitutes the first critical element of cladding-pumped fiber lasers, since efficient signal conversion is directly correlated with the amount of pump power that can be launched [1]. The second important consideration is to improve the pump absorption so that skew rays do cross through the core. This issue has been approached by varying the geometry of the inner cladding of the fiber to effectively reduce the fiber length by increasing the absorption [2]. These concerns are key points of consideration for modern designers who seek to obtain an efficient fiber laser. Last year, a *cw* fiber laser with an output power of 1.36 KW was demonstrated [3], revealing the potential of the CPFL design.

An attractive feature of rare-earth doped silica–based fibers is that they provide a very broad fluorescent (broad emission linewidth), thus offering the potential of broad tunable laser operation. Typically, conventional bulk solid-state lasers, which are the counterpart of fiber lasers, use crystalline hosts that exhibit large gain efficiency and good thermo-mechanical properties. However, crystalline hosts have narrow linewidths, restricting the wavelength range of operation and hence their applicability as a tunable device. Thus, power scalability and wide wavelength tunability are features that are largely exclusive to CPFLs [4]. In addition to these features, tunable fiber lasers are also compact and have output power ranging up to the level of watts, making them very attractive for a number of applications.

In this paper, a novel tunable fiber laser is demonstrated in which the wavelength selectivity is realized by adjusting the separation between a broadband mirror and the fiber facet of a 15 mm long, 105/125 μm multimode fiber (MMF). The MMF is spliced to a single-mode fiber (SMF) which is connected to the active double-clad Ytterbium doped fiber. The length of the MMF is slightly shorter than the length where the output light distribution of the SMF is re-imaged, which is the point where the broadband mirror is located. Due to the wavelength dependence of the re-image, the position of the re-imaging plane will depend on the wavelength, and the laser wavelength can therefore be tuned by varying the distance between the MMF facet and the broadband mirror. Using this principle, the tunable fiber laser revealed a tunability of 8 nm, ranging from 1088-1097 nm, and an output power of 500 mW. The simplicity of the setup makes this tunable laser very cost-effective.

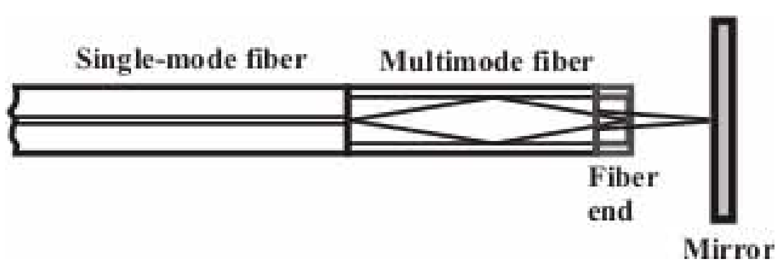

Fig. 1. Schematic diagram of the components of the wavelength tuning device.

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2. Tuning mechanism

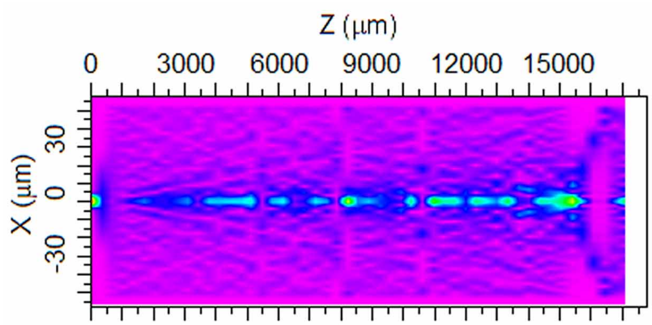
Figure 1 shows a schematic representation of the wavelength tuning device and its components. The output signal from the SMF enters into the MMF, and high order modes are excited within the MMF. Interference between these modes will give rise to the formation of single images of the SMF output signal at periodical intervals along the axis of the MMF. This is a well known effect that occurs in multimode waveguides, and has been widely used to demonstrate several integrated devices [5,6]. The length at which single images are formed can be obtained from the restricted symmetric interference condition which is given by

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

where L_π is the beat length

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

Here n_{MMF} and W_{MMF} correspond respectively to the refractive index and diameter of the MMF core, with λ_0 as the free-space wavelength. Figure 2(a) shows the results from the numerical simulations of the light propagation along a MMF with a core diameter of 105 μm (NA~0.22). As can be observed, for this case the first re-imaging point occurs at a distance of ~15.2 mm, which is the position where the intensity distribution converge or is focused onto an on-axis point. If we cleave the MMF at a length slightly shorter than the re-imaging distance, the light exiting the fiber converges to a point beyond the fiber facet (in air), or focuses to a plane.



(a)

(b)

Fig. 2. (a) Numerical calculation of the beam propagation along a piece of 105/125 μm multimode fiber and (b) Photograph of the interference pattern at the end of the fiber facet.

In our experiments, the MMF was cleaved at a distance of 15 mm and the light is launched into the MMF using a SMF at a wavelength around 1080 nm. If a broad spectrum is launched into the MMF, instead of a single wavelength, each wavelength will form its own re-image at a different location along the fiber axis. Figure 2(b) shows a photograph of the interference pattern from the MMF at one of the re-imaging planes. If a mirror is placed at this free-space location where the re-imaging point occurs, the coupling of the light reflected back into the fiber would be at a maximum compared with any other location in the near vicinity (see Fig. 1). Since the re-imaging position is found to be wavelength dependent, different mirror positions along the axis of the fiber will correspond to different retroreflection maxima, each for a particular wavelength. When the mirror is positioned at one of these maxima, the light at the associated wavelength will be reflected while the rest of the gain spectrum is attenuated. Hence, this effect can be used to select one particular wavelength from a broad spectrum by simple changing the position of the mirror. As noted, a broadband mirror is required in order to operate the device over a wide wavelength range.

A similar concept has been used in a tunable laser where the cavity loss was large over the entire gain bandwidth, except near the desired laser operating wavelength. For example, the work done by Nilsson and co-workers [4], showed the tunability of different rare earth doped fiber lasers using bulk gratings as the tuning mechanism. Although this provides an efficient tuning device, the complete system becomes very bulky and costly.

3. Experimental layout and results

Figure 3 shows the experimental setup for the wavelength tunable double-clad fiber laser. It consists of a double-clad Ytterbium-doped fiber (DCYDF) with a core/cladding diameter of 6/125 μm and a 0.14/0.45 numerical aperture [7]. The length of the DCYDF was 16 m, which corresponds to 7.2 dB of pump absorption (only ~80 % of the pump light is absorbed by the active core). The DCYDF is end-pumped by a fiber pig-tailed multi-mode laser diode with 3 W of fiber-coupled output power at a wavelength of 915 nm. The pump light was launched into the YDF via a focusing lens as can be seen in Fig. 3. The lens was AR coated with a broadband coating covering the pump wavelength. The end of the DCYDF used for pumping was perpendicularly cleaved to provide feedback for laser oscillation, and also to operate as the output coupler for the laser. The other end of the fiber was spliced to the tuning mechanism. As we described before, this mechanism consisted of two different fibers spliced one to each other, with the SMF end spliced to the DCYDF. The single mode fiber also acts as a pump filter since the non-absorbed pump power is filtered out by the non-guiding structure formed by the cladding of the SMF and its high index protective polymer. A dichroic mirror placed between the fiber pigtailed laser and the DCYDF is used to separate the laser output from the path of the pump beam.

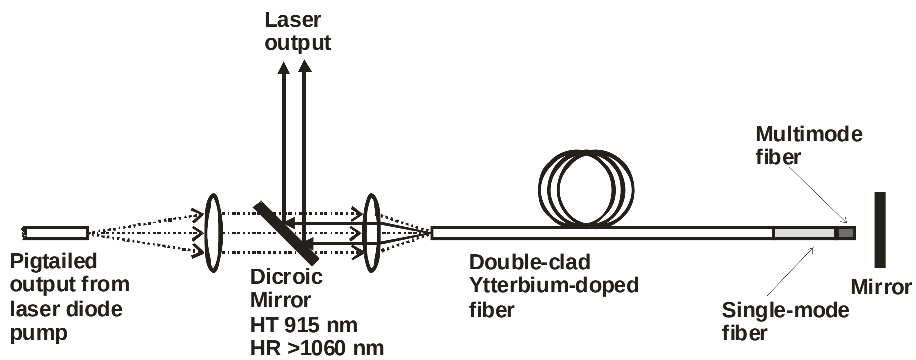


Fig. 3. Configuration of the tunable double-clad Ytterbium-doped fiber laser.

We then evaluated the characteristics of this very simple laser cavity. First we identified the focal plane of the re-imaging that was closest to the output facet of the MMF. The broadband mirror was placed at this position, and wavelength tuning was realized by varying the distance between the broadband mirror and the output facet of the MMF. This was easily accomplished by fixing the tuning device and longitudinally moving the mirror. The mirror was then moved away from the MMF in 25 microns steps, and the output power and optical spectrum of the tunable laser were measured at every step. The optical spectrum analyzer revealed a wavelength tuning range of 8 nm ranging from 1088 to 1097 nm. The tuning characteristics were almost flat, as shown in Fig. 4, with a measured linewidth down to 0.5 nm and a signal-to-noise ratio better than 30 dB over the tuning range. For clarity, only the emission spectrums of four different lasing wavelengths are shown. The flat spectral response in our multimode interference (MMI) filter is a direct consequence of the mirror shift, which effectively changes the length of the MMI region. In a typical MMI device the length of the

MMI region is usually fixed. Therefore, when a wavelength scan is performed, it exhibits a non-flat response because it is optimized at some specific wavelength. In our case, at every mirror position, the MMI filter selects the wavelength with the maximum signal strength, providing a flat spectral response. The output power of the system as a function of wavelength is also plotted in Fig. 5. An average optical power of 500 mW was obtained, with the minimum and maximum power being 460 and 550 mW, respectively. Also plotted on the right hand side scale of the graph is the separation between the mirror and the MMF for each wavelength measured. It can be noticed that for separation distances shorter than 100 micron and longer than 250 microns the lasing emission vanished and does not correlate to the emission cross section spectrum of the Yb ions. This was related to different factors such as the use of a broadband mirror that was not optimized for this particular wavelength range, and additional excessive loss generated in the SMF-MMF splice point (>3 dB).

At normal incidence the mirror has a peak reflectivity >95% in the range from 1100-1320 nm. From 1100 nm to 1070 nm the mirror reflectivity drops from ~93% to ~73% as can be observed in the inset of the Fig. 4. On the other hand, the fluorescence peak for the Ytterbium doped fiber occurs at ~1082 nm, for the fiber length used in the experiment. Since the lasing wavelength is determined by the round trip gain-loss, in our experimental setup this is related to the mirror reflectivities, splice losses, and gain spectra of the active fiber. Therefore, in our laser the mirror reflectivity is too low to obtain lasing below 1088 nm, while the length of the fiber is too short to obtain enough gain at wavelengths longer than 1097 nm. These effects are only enhanced by the additional splicing losses. If we want to extend the tuning range we need to use a mirror with a flat spectral response within the Yb gain spectra in order to take advantage of the whole gain range of Yterbium-doped fibers. According to numerical estimations, a tuning range wider than 30 nm should be attainable with this wavelength tuning device [8], making it an inexpensive tuning mechanism. The only issue in this case concerns the alignment between the MMF and the broadband mirror, which can be a tedious work. However, work is underway to improve our tuning device using a self-alignment scheme employing a capillary tube. Nevertheless, our set up demonstrates the simplicity of the tuning mechanism by successfully tuning the laser around the 1.08 microns regime without any significant difficulty. In the literature, many techniques to tune over, as well as to generate, multiple laser wavelengths have been presented. However, those techniques are oriented toward telecomm applications, and they are therefore technically complex [9]. Recently, a multimode fiber Bragg grating (MMFBG) was used as the tuning mechanism of a fiber laser [10,11]. Although the device is very promising, a Bragg grating has to be fabricated in the MMF. Our device is also based on a MMF, but no grating has to be induced, thus reducing the complexity of the fiber laser.

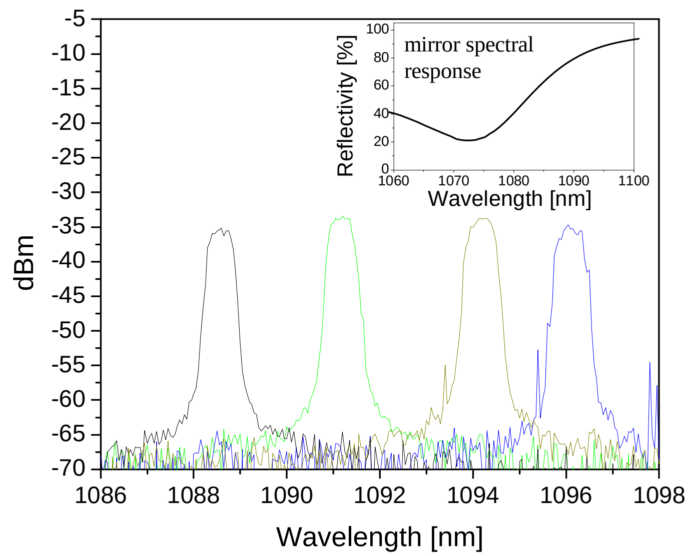


Fig. 4. Tuning characteristics of the double-clad Yb-doped fiber laser using our multimode interference tuning device. (Inset: The reflection response of the dichroic mirror)

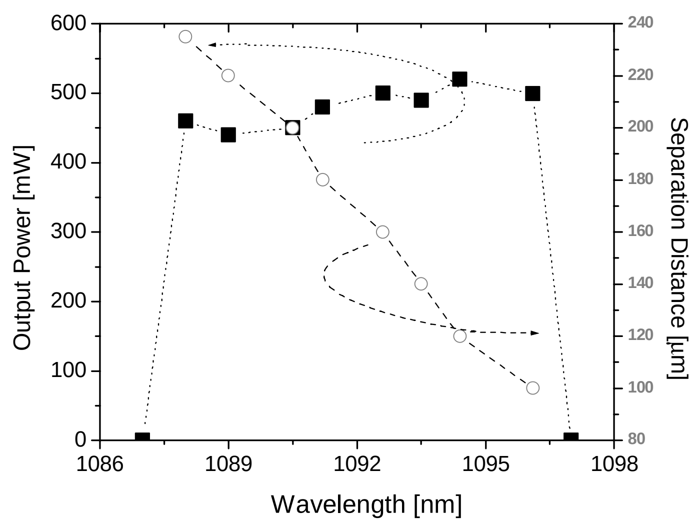


Fig. 5. Output power vs. tuning wavelength range for our novel tunable YDFL (square) and separation distance of the mirror vs. tuning wavelength for the novel tunable YDFL (circle).

For the strongest emission wavelength, we measured the slope efficiency of the laser. This was realized by changing the current of the fiber pigtailed diode pump laser and measuring the output power from the DCYDF laser. This is shown in Fig. 6, from which a slope efficiency of roughly 26% wrt. launched pump power is obtained.

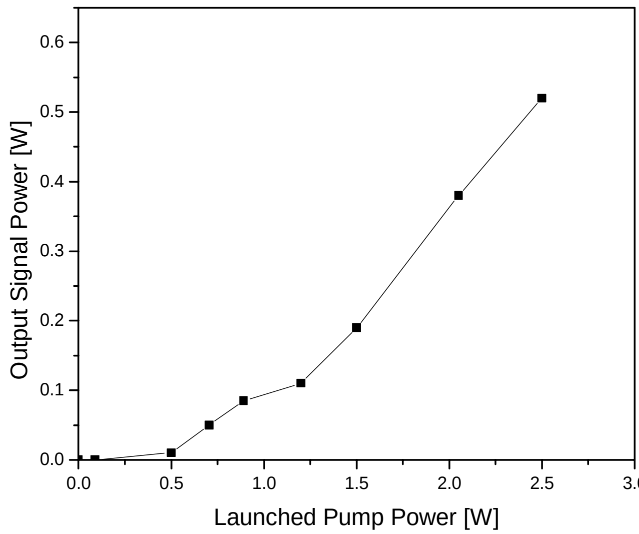


Fig. 6. Output laser power at 1094.5 nm as a function of the current driver at 915 nm in a double ytterbium doped fiber.

Since we were limited by pump power it is clear that even more pump power could be converted into signal power. Regarding the tuning mechanism, the only drawback is related to the instabilities produced by the mechanical noise in the optical bread-board. However, it was considerably reduced when the tuning mechanism was isolated from the rest of the system, and should not be an issue in our improved system where a capillary tube will be used for the alignment. The most important advantage of this system is without any doubt the simplicity and the low number of components that were used. This makes our DCYDF tunable laser a very cost-effective system when compared to other tunable laser systems.

4. Conclusions

In conclusion, we have investigated the performance of a novel tuning mechanism that operates by employing the self-imaging properties of MMF. The device is relatively simple and inexpensive because it only requires a minimal number of readily accessible components. This tuning device was then used in an ytterbium doped fiber laser that operates around the 1.08 μm spectral region. A tuning range of 8 nm, which extended from 1088 to 1097 nm with a flat emission, was demonstrated. Significant output power levels of up to 500 mW with an optical power conversion efficiency of 26% were also measured. These results demonstrate the potential of our wavelength tuning device. Significant improvement is expected from the optimization of some elements in our system. In addition, a more robust system is anticipated due to a new method which allows for the self-alignment of the MMF and the broadband mirror. Irregardless, the simplicity of the cavity makes this a very cost-effective tunable laser.

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