Co-lasing in an electrically tunable erbium-doped fiber laser

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We demonstrate simultaneous wavelength operation (co-lasing) of an erbium-doped fiber ring laser with independent tunability of each wavelength over 35 nm between 1528 and 1563 nm. We study two different configurations and also investigate use of aluminum versus germanium codoped gain modules in the ring. We find that the aluminum codoped gain module has superior tunability.

Future fiber optic communications systems will utilize wavelength division mutliplexing as a means of transmitting more information over the same number of fibers. A single source capable of generating multiple frequencies simultaneously would be an attractive option for such systems. We report here on an all-fiber, dual-frequency, co-lasing, widely tunable laser source with the potential for multifrequency co-lasing operation. A dual-frequency co-lasing source could also be used for variable difference frequency generation.

We recently reported an all-fiber, low-threshold, widely tunable single-frequency, erbium-doped fiber ring laser with a tandem Fabry–Perot filter,[1-3] having interesting noise and spectral properties. These lasers are stable single-frequency sources in the 1.55 μm telecommunications window. Similar devices have shown linewidths as narrow as 1.4 kHz.[4] The dual-frequency, co-lasing, widely tunable laser source is constructed from essentially the same components as the single-frequency source. By using a single ring, however, a reduction in the number of components that would be needed to construct two separate, single-frequency sources is achieved.

Two experimental configurations for obtaining co-lasing operation were investigated. They are shown in Figs. 1(a) and 1(b). In Fig. 1(a) we see the single-gain module configuration. The gain module (*G*) is a commercial erbium-doped fiber amplifier consisting of approximately 20 m of fiber. The index-raising codopants included aluminum. The erbium-doped fiber amplifier was pumped with a 980-nm laser diode and provided up to 37.2 dB of small signal gain and 10.3 dBm of maximum output power at 1532 nm. We did not have quantitative measurements of the gain as a function of wavelength, however, it was possible to achieve lasing over the entire region accessible with the tuning filters.

The isolators (ISO) had less than 1 dB of forward loss and provided up to 37 dB of peak isolation in the wavelength range of interest. The polarizer (POL) was a plasmon-wave-type device, pigtailed with polarization preserving fiber. It had less than 1 dB of loss in the allowed polarization and 24 dB of loss in the orthogonal polarization. The two polarization controllers (PC) consisted of three quarter-wave plates made by winding fiber around three disks which could be rotated independently of each other. They had less than 1 dB of loss.

The two tuning filters were placed in the arms of a Mach–Zehnder interferometer created by two 3 dB fused-fiber couplers. A calculation discussed below showed that the minimum frequency separation between the co-lasing frequencies was limited by the bandwidth of the tuning filters. The tuning filters were broadband Micron Optics fiber Fabry–Perot filters (BB FFP). One had a free spectral range (FSR) of 4020 GHz, a bandwidth of 26.1 GHz, and an insertion loss of less than 3 dB. The other had a FSR of 4700 GHz, a bandwidth of 38.2 GHz and an insertion loss of less than 2 dB. We estimate that the total cavity length for either one of the two wavelengths was approximately 40 m corresponding to a mode spacing of 5 MHz. The total minimum loss seen by one wavelength was about 12 dB

Co-lasing was achieved by tuning the BB FFPs to the desired wavelengths and then using the polarization controllers in combination with the polarizer to balance the losses with the amplifier gain. Output from the laser was split by a 3 dB coupler. Half the output was sent to a spectrometer and the other half to a scanning Fabry–Perot interferometer (Newport Research Super-Cavity SR-170 FSR 6 GHz, resolution 1 MHz).

The supercavity Fabry–Perot interferometer showed that the configuration in Fig. 1(a) operated with only one longitudinal mode excited at each wavelength (see Fig. 2). The smaller peaks in the picture are transverse modes of the supercavity Fabry–Perot. Figure 3 shows a plot of the

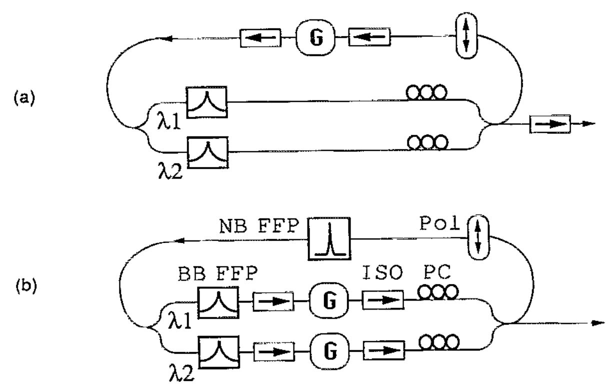

FIG. 1. Laser configurations used in co-lasing experiments. (a) single-gain media configuration, (b) dual-gain media configuration. G: gain module, Pol: plasmon wave polarizer, NB FFP: narrow-band fiber Fabry–Perot filter, BB FFP: broadband fiber Fabry–Perot filter, ISO: isolator, PC: polarization controller.

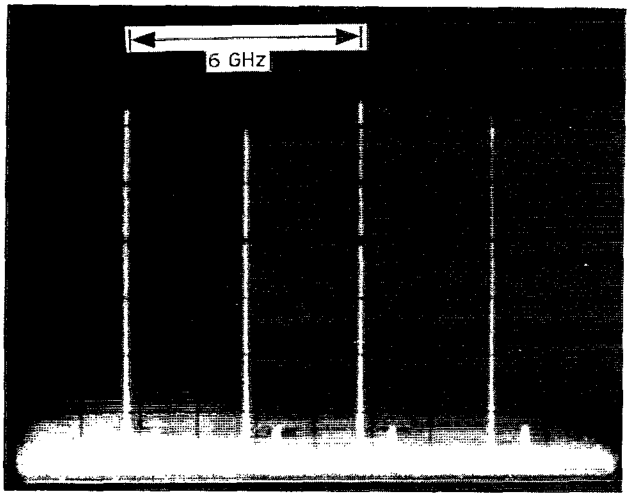

FIG. 2. Typical output of the Newport Supercavity spectrum analyzer, showing two co-lasing modes separated by several nanometers in wavelength but folded over by the 6 GHz FSR of the supercavity. The smaller peaks are the transverse modes of the supercavity.

achievable tuning range for this configuration measured using the grating spectrometer. Each point on the graph represents one measured spectrum taken with FFP voltages fixed. Tuning was limited only by the free-spectral range of the BB FFPs. Some difficulty in tuning was encountered around 1537 nm. We believe this is due to a system idiosyncrasy currently under investigation. When the filters were tuned into the same wavelength region and close enough in wavelength to create significant bandpass overlap (proximity tuning), a Mach–Zehnder effect occurred reducing apparent cavity loss to about 5 dB for a single mode. In this case the laser reverted to single-frequency operation.

Maximum output power per wavelength for co-lasing operation was approximately 200 μW. For proximity-tuning induced single-wavelength operation, the power into the single-lasing mode increased by more than $2\times$ as compared to the power per mode measured for co-lasing operation. This increase was the result of the obvious increase (by approximately $2\times$) in the quantum efficiency per mode and a decrease in lasing threshold caused by the

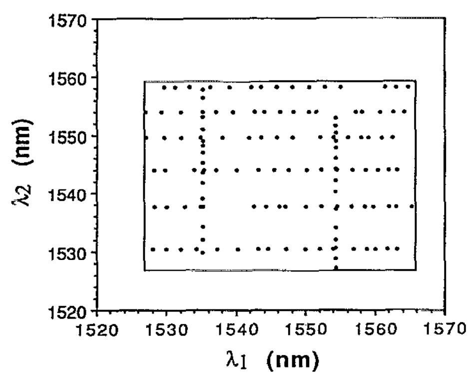

FIG. 3. Experimental tuning data from configuration in Fig. 1(a). Co-lasing was observed at each point on the graph.

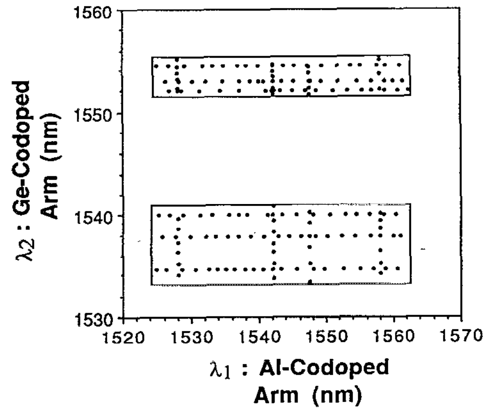

FIG. 4. Experimental tuning data from configuration in Fig. 1(b). Co-lasing was observed at each point on the graph.

apparent reduction in Mach–Zehnder loss mentioned above.

Figure 1(b) shows the other configuration investigated. It contained two gain modules: the first being the module used above and the second gain module similar to the first, however, with a pure germanium index-raising codopant (i.e., no aluminum). The second gain module had a small signal gain of 40.0 dB and a maximum output power of 8.43 dBm at 1536 nm. Tuning for this device was limited by the bandwidth of the second gain module. The configuration in Fig. 1(b) also contains a narrow band (NB) FFP filter. This device has a free spectral range of 10.4 GHz, a bandwidth of 130 MHz, and an insertion loss of 4 dB. It also has some polarization dependence due to its long cavity length and high finesse, making the apparent fiber-induced birefringence significant. The use of tandem FFP filters for improved wavelength selection is described in greater detail in Refs. 1, 2, and 3.

One of the advantages of the dual amplifier configuration is that there is no power sharing between modes. A further advantage of this configuration is that there is no need to adjust the polarization controllers to balance the gain and loss. The gain modules see only one narrow wavelength range and they dynamically adjust to balance the loss. With the NB FFP in place, the lasing modes have stability similar to that reported in Refs. 2 and 3. However, due to the narrower gain bandwidth associated with the germanium only codoped versus the aluminum codoped gain module, the tuning area is reduced (see Fig. 4). It is apparent that the smaller gain bandwidth of the germanium codoped amplifier provided sufficient gain to achieve lasing only in the region 1533 to 1541 nm around the 1537 nm gain peak and in the region 1551 to 1555 nm around the 1555 nm gain peak. The tuning range could be improved by using two aluminum codoped gain modules. Another aluminum codoped gain module was not available at the time of this experiment. Lowering the cavity loss would also increase the tuning range.

Proximity tuning was again restricted by the finite bandwidth of the BB FFP. We have investigated this phenomena theoretically by considering transmission through

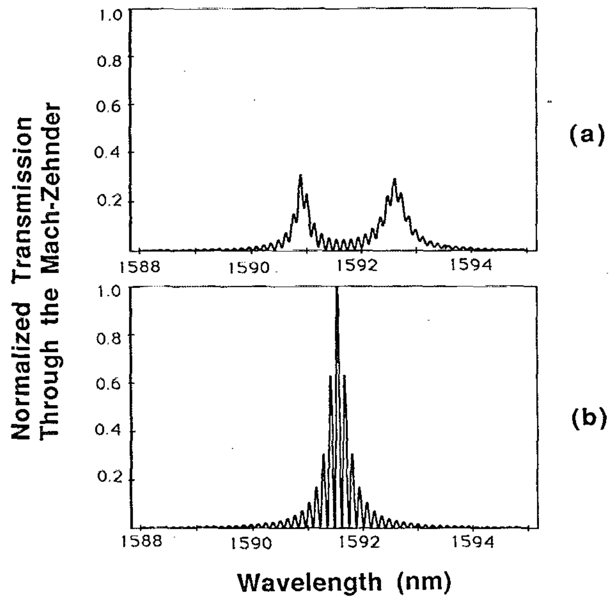

FIG. 5. Theoretical calculations of Mach–Zehnder throughput. (a) Nonproximity tuning and (b) proximity tuning.

a Mach–Zehnder interferometer with Fabry–Perot interferometers in its arms. Two cases are considered: nonoverlapping FFP filter resonances and overlapping FFP filter resonances. By using parameters characteristic of our fiber Fabry–Perot filters and assuming a 12-cm path length difference for the Mach–Zehnder (the path length difference for the experimental case was not easy to determine with great accuracy but was close to this value) the transmissioin spectra shown in Fig. 5 were generated. Figure 5(a) is an example of nonproximity tuning, showing no serious deformation of the individual peaks. Co-lasing could be achieved in this regime. Figure 5(b) is an example of proximity tuning and the resulting interference effects. Single-mode operation would be favored in this case. In these plots, unity is full transmission through the interferometer and insertion loss due to the BB FFPs was not included in this simple calculation.

In conclusion, we have demonstrated widely tunable, co-lasing operation of an all-fiber, erbium-doped ring laser in the 1.55 μm telecommunications window, both with a single- and double-gain module configuration. We look forward to continuing this work by investigating the potential of multifrequency operation, broader tuning, and application of narrower bandwidth FFPs.

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