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1 W tunable dual-wavelength emission from cascaded distributed feedback fiber lasers

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We present experimental results of cascaded distributed feedback fiber lasers that generate up to 1 W continuous-wave dual-wavelength emission at room temperature. The complete laser device is integrated into a 10-cm-long active phosphate glass fiber with two phase-shifted gratings inscribed. The distributed feedback fiber lasers are cladding pumped by multimode laser diodes, in contrast to conventional core pumping with single-mode diodes. Tuning of the emission wavelength is also demonstrated. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2840998]

Spectrally narrow dual-wavelength fiber lasers have attracted extensive research interests for applications in optical communications, sensing, ranging, high-resolution spectroscopy, and nonlinear optical processes such as terahertz generation.[1–8] While high-level output power is desirable for many applications, it is particularly important at the telecom wavelength of ~1.5 μm and as optical pump source for nonlinear wavelength conversion such as terahertz emission.[7,8] All previous approaches to achieve stable, narrow-linewidth, dual-wavelength emission are exclusively core pumped with single-mode diode lasers,[1–6] limiting the maximum output power to well below 100 mW. To elevate the signal power to the next level, e.g., by an order of magnitude or more, powerful yet affordable multimode laser diodes are required and cladding-pumping scheme has to be applied, as commonly practiced for high-power fiber lasers. In previous approaches, where active double-cladded fibers were pumped with multimode diodes to achieve high-power simultaneous multiwavelength lasing, they were either unstable[9] or lacking control and tunability of the emitted wavelengths.[10]

In this letter, we demonstrate compact cladding-pumped distributed feedback (DFB) fiber lasers that emit simultaneously at two closely spaced wavelengths at room temperature. The complete laser device is built into a short piece of $Er^{3+}-Yb^{3+}$-codoped phosphate glass fiber that is only ~10 cm in length. The dual-wavelength laser emission is enabled by a pair of phase-shifted gratings (PSGs) written directly into the active fiber. When the grating-inscribed phosphate fiber is spliced to a multimode fiber that delivers the pump light, we demonstrate a cladding-pumped cascaded DFB fiber laser with dual-wavelength emission. Moreover, when an external mirror is added and served as the mutual high reflector for both DFB structures, elevated output power as well as improved emission homogeneity has been obtained. The 1 W output power from this laser device is the highest demonstrated from a dual-wavelength fiber laser at ~1.5 μm. Tuning of the separation between the two wavelengths has also been achieved.

Phosphate glass fibers have been well known for their high solubility to rare-earth ions, which enables very compact high-power fiber lasers.[11–13] However, phosphate fibers generally lack photosensitivity and to achieve narrow-linewidth laser emission with fiber Bragg gratings (FBGs), active phosphate fibers have to be spliced to FBG-inscribed silica fibers that result in hybrid fiber devices.[12,13] However, the spliced joints between the two different fibers may cause high loss and mechanical fragility at high power operation because phosphate and silica glasses have substantially different optical, mechanical, and thermal properties. It is thus beneficial to incorporate all functionalities into only the phosphate fiber without employing silica fibers, which results in compact spliceless all-fiber lasers desirable for robust high power operation. Strong FBGs written directly into phosphate fibers by 193 nm ArF excimer laser with phase masks have been reported recently.[14] Furthermore, PSGs have been written into active phosphate fibers to demonstrate cladding-pumped DFB fiber lasers with multimode pump diodes.[15] This enables a direct approach to implement high-power multiwavelength fiber lasers by cascading multiple DFB structures into a single active fiber and taking advantage of the potent multimode pump power that cannot be completely absorbed by one DFB resonator. Therefore, cascaded cladding-pumped DFB fiber lasers emitting at either single or multiple wavelengths are in principle accomplishable with multimode pump diodes and demonstrated here.

The gratings utilized for our DFB fiber lasers have an asymmetric structure: a 50 μm wide gap (defect) is placed inside a 3.5-cm-long otherwise uniform grating, as shown in Fig. 1, and the defect is off the center so that the two grating ends have different reflectivities.[15] This design is to introduce both the phase change and directionality for single-wavelength unidirectional DFB laser emission, with the pump light injected from the high reflectivity (R_1) grating end and the signal exited at the low reflectivity (R_2) end. However, the signal light is still bidirectional if R_1 is not highly reflective. Furthermore, in a cascaded unidirectional DFB fiber laser, intensity inhomogeneity among different

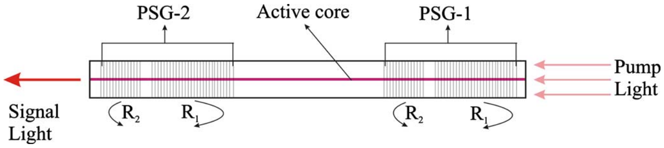

FIG. 1. (Color online) Illustration of the cladding-pumped cascaded DFB fiber laser (lengths not to scale).

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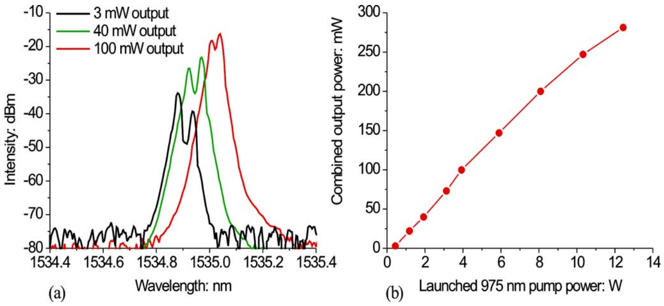

FIG. 2. (Color online) Dual-wavelength cascaded DFB fiber laser: (a) emission spectra at different output levels; (b) signal vs pump power plot.

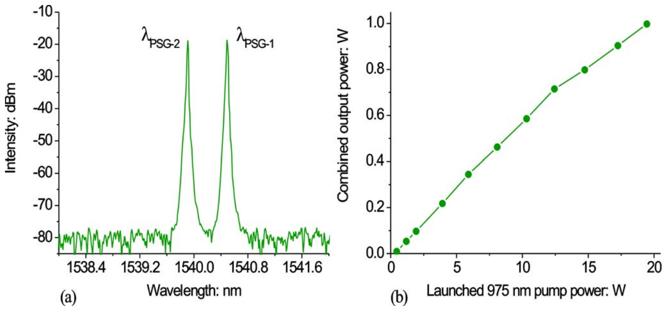

FIG. 3. (Color online) Dual-wavelength cascaded DFB fiber laser with an external reflector: (a) output spectrum at ~500 mW output power; (b) signal vs pump power plot.

wavelengths inherently exists. This is because each DFB resonator completes itself within its periodic structure and different wavelength passes different active lengths. This inhomogeneity cannot be eliminated even with a dual-end pumping scheme. However, if we insert an external broadband high reflector at the pump end in addition to the DFB structures, it not only decides the directionality of the emission[16] and reduces the lasing threshold[17] but may also improve the intensity homogeneity among different wavelengths. It serves as the mutual high reflector for all resonators, and it overlaps and couples multiple linear cavities inside the active medium.

In our experiments, the phosphate glass fiber has an outer diameter of 125 μm and a 9 μm diameter single-mode core that is codoped with 1 wt % Er_2O_3 and 8 wt % Yb_2O_3. The active fiber has a total length of ~10 cm and two identical PSGs are written in the fiber by 193 nm laser exposure. Both gratings are manufactured by illuminating with the same phase mask; however, minor variance during manufacturing always introduces a slight shift between the two actual resonant peaks that is exploited to generate the two-wavelength emission. The proposed fiber device is illustrated in Fig. 1. The first grating (PSG-1) is located at the pump-launching end and the second (PSG-2) is placed ~3 cm away from PSG-1. The output fiber end is angle cleaved to eliminate back reflection.

Dual-wavelength fiber lasers are constructed by two approaches with this grating-pair-embedded active fiber. In the first approach, two PSGs with nominal reflection peaks at 1535 nm are written into the fiber. The pump-launching end of this fiber is spliced to a multimode fiber that delivers the pump light. Since neither the angle-cleaved output facet nor the spliced joint provides feedback, and the two PSGs have different resonant peaks, this fiber device works indisputably as a cascaded DFB laser. The active phosphate fiber is clamped into a heat sink to remove the excessive heat. The fiber laser emits simultaneously at two wavelengths with a lasing threshold of <400 mW when pumped with 975 nm multimode laser diodes. It generates up to 280 mW output power at 12.5 W pump power and has a slope efficiency (SE) of ~2.5% with respect to the launched pump power. Figure 2(a) shows several emission spectra at different output levels and Fig. 2(b) plots the signal versus pump power. We have confirmed that the double emission lines agree with the individual resonant peaks of the two PSGs, respectively. Both emission peaks have a 3 dB linewidth well below the resolution of the optical spectrum analyzer used (Ando AQ-6317 with resolution bandwidth limit of 0.01 nm) and cannot be further resolved; however, the linewidth of such a cladding-pumped single DFB fiber laser has been determined to be 50 kHz or less by self-delayed homodyne measurements.[15] The wavelength spacing between the two emission peaks varies at different output levels, as shown in Fig. 2(a), and the obtained minimum spacing is 0.03 nm at 100 mW output, which is less than the reported smallest spacing of 0.05 nm from a room temperature dual-wavelength fiber laser.[5] It is possible to further reduce the wavelength spacing by optimizing the grating design and fabrication process, e.g., by lowering the refractive index modulation amplitude and increasing the total length of the grating. Both would result in narrower reflection bandwidth of the gratings, which, in turn, will shrink the wavelength separation. It is noted that the intensity inhomogeneity of the two emission peaks is >2 dB.

To enhance the laser efficiency and emission homogeneity, in the second approach, another 10-cm-long active phosphate fiber is prepared with two inscribed PSGs of nominal resonant peaks at 1540 nm. This fiber device is first tested with the previous scheme, resulting in a second dual-wavelength DFB fiber laser emitting at ~1540 nm with a SE of ~1.7%. Next, the pump end of this active fiber is cleaved and butted against a multimode pump delivery fiber that has a dielectric mirror deposited on its facet. The broadband mirror is transparent at the pump wavelength and highly reflective at the signal wavelength; it thus serves as the high reflector for both DFB resonators. Utilizing the same pump source, robust simultaneous dual-wavelength emission is observed from the lasing threshold of <400 mW to ~20 W of pump power, where a maximum of 1 W output power is achieved in this third DFB fiber laser. A typical output spectrum is shown in Fig. 3(a) and a wider wavelength spacing (~0.5 nm) is observed. The signal versus pump power plot is shown in Fig. 3(b). Although a reduced lasing threshold is not clearly observed, the SE increases to ~5.5% with respect to the launched pump power, which more than doubles that of the ~1535 nm DFB fiber laser (without external reflector) even the ~1540 nm emission is off the gain peak of the active glass. It shall be noted that the laser linewidth is again below the optical specrtrum analyzer's resolution of 0.01 nm; meanwhile, the intensity inhomogeneity of the two emission peaks improves to be <1 dB, as shown in Fig. 3(a).

The two emission peaks of our DFB fiber lasers can be, in principle, independently tuned. Utilizing the third DFB fiber laser, the PSG-2 that initially emits at the shorter wavelength in Fig. 3(a) is attached to a thermoelectric cooler and the PSG-1 is clamped into the heat sink to maintain a constant temperature. The initial wavelength spacing is 0.35 nm

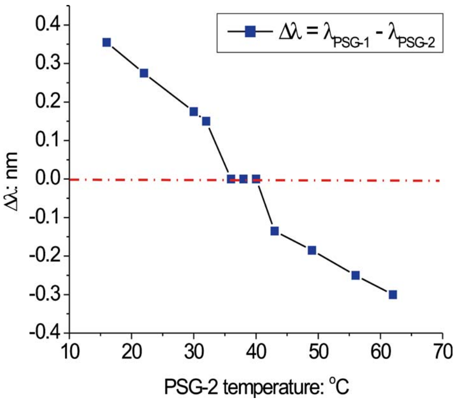

FIG. 4. (Color online) Tuning of the wavelength separation: PSG-2 is heated up and PSG-1 is kept at constant temperature.

at an output level of ~100 mW. As the temperature of PSG-2 is gradually increased, its resonant peak redshifts and the wavelength spacing shrinks until the emission spectra collapse into a single line. Referring to Fig. 4, we note that the spacing cannot be tuned infinitesimally with this temperature adjusting process, and we observe a sudden "lock-in" of the emitting wavelength when the separation is 0.15 nm or less; although smaller values have been achieved from the previous ~1535 nm DFB fiber laser. When the temperature is further increased, the PSG-2 emits at a longer wavelength and it moves at a slightly slower pace than before the collapsing happens.

To conclude, we have presented the design, fabrication, and performance of high-power dual-wavelength cascaded DFB fiber lasers. The laser device is completely built into a short piece of active phosphate fiber with a pair of phase-shifted asymmetric gratings imprinted, employing no silica fiber components. By utilizing high-power multimode pump diodes, we have demonstrated narrow-linewidth dual-wavelength laser emissions from cladding-pumped cascaded DFB fiber lasers and achieved 1 W combined output power with wavelength tunability.

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