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TUNABLE, SINGLE-FREQUENCY Er:Yb PHOSPHO-SILICATE FIBER FABRY-PEROT LASERS

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Abstract Tunable erbium:ytterbium phospho-silicate fiber lasers using single and compound fiber Fabry-Perot configurations are reported for the first time. Continuous tuning of an ultrashort-cavity laser over 3.33nm and discrete tuning of longer compound-cavity lasers over 5nm are demonstrated.

Introduction Erbium fiber lasers emitting in the 1.55um wavelength region are useful for applications in telecommunications, spectroscopy and fiber sensors. Single-mode fiber lasers constructed with either Fabry-Perot (FP) or ring cavities usually require wavelength filtering components such as external gratings [1], in-fiber gratings [2], and Fabry-Perot filters [3],[4]. Wavelength tuning can subsequently be achieved by filter adjustments. To ensure stable single-frequency lasing and environmental stability, it is important that laser cavities be short, simple and compact. Recently an ultrashort erbium:ytterbium (Er:Yb) phosphate-glass fiber Fabry-Perot (FFP) laser (cavity length: 100um) has demonstrated stable single-mode tunability without any additional filtering [5]. On the other hand, Er:Yb phospho-silicate (P-Si) fibers have shown excellent qualities as fiber power-amplifiers [6] and lasers [2], and by adopting such a fiber within a FFP cavity, continuous wavelength-tuning and single-mode operations with very short cavity lengths are reported herein. The attractive features of Er:Yb P-Si fiber include efficient pump absorption at 980nm by the Yb ions, a large stimulated emission cross-section for the Er, wider gain peak than that of the phosphate-glass fiber, and mechanical properties similar to regular silica fibers. Note that the increased pump absorption afforded by Yb is essential for the construction of short laser resonators, since the pump absorption in short fiber lasers containing Er only is about two orders of magnitude lower than with Yb included.

Stable single longitudinal-mode laser operation can be obtained when the FP mode spacing of a short resonator is large relative to the gain bandwidth such that only one mode acquires sufficient gain to reach lasing threshold. Continuous wavelength-tuning can then be achieved by piezoelectric tuning of the FP cavity length. Because a wide tuning range requires a short cavity length with low loss, FFP technology [7] enables very short cavities (~8um) and very high cold-cavity finesse to be achieved in a convenient, tunable package, thus allowing the use of sub-mm fiber lengths in which the single-pass gain required is <0.1dB. Here we demonstrate the shortest Er:Yb P-Si FFP laser ever reported, having a 142um cavity length and a continuous wavelength tuning range over 1.45nm.

In addition to the single-cavity design, FFP technology offers the unique capability of fabricating short compound-cavity fiber lasers which we demonstrate to provide higher output power and discrete wavelength tuning ranges comparable or wider than those affordable by ultrashort single-cavity lasers.

Experiments A single-cavity FFP laser with length l and a compound-cavity FFP laser with lengths l_1 and l_2 are sketched in Fig.1(a) and (b) respectively. The laser cavity is mounted in a piezoelectric transducer (PZT) stage capable of tuning the air-gap. Characteristics of the P-Si fiber are: Er:Yb dopant concentrations of 1000:12800 ppm, respectively, a cut-off near 1120nm, and an effective emission cross-section of $5.68\times10^{-25}(m^2)$. The minimum cavity length for laser action with 99.9% mirrors is calculated to be ~80um, assuming no intra-cavity loss. If we assume a realistic passive-cavity single-transit loss of 0.0006, the minimum length for the P-Si FFP laser becomes ~128um.

Stable single-frequency lasing was obtained for fiber lengths of 513um, 208um, and 142um using 99.9% input/output mirrors. Table 1 lists the respective performances such as the slope efficiency (SE), maximum output power (P_m) (measured at a pump power P_p=32mW before saturation), relaxation oscillation frequency (f_r) and its corresponding modulation depth (mod), and wavelength tuning range ($D\lambda$). Fig.2 shows the laser output versus pump power curves for all three lasers. The saturation behavior was observed for all FFP lasers and is suspected to be due to either thermal effects or fundamental spectroscopic limitations. The l=208um laser was capable of continuous wavelength-tuning over 3.33nm, which corresponds to 88% of the resonator's free spectral range (FSR), and Fig.3(a) shows the tuning range displayed at 9 wavelengths.

Table 1: Single-cavity FFP laser performance

R1(%)	l(um)	R2(%)	SE(%)	P_m(uW)	f_r(MHz)	mod(%)	$D\lambda$ (nm)
99.9	**513**	99.9	0.06	19	1.3	0.47	N/A
99.9	**208**	99.9	0.05	16	0.995	0.71	3.33
99.9	**142**	99.9	0.01	3.1	0.475	7	1.45

The shortest laser (l=142um) exhibited both single-mode and single-polarization characteristics. Apparently the gain at this fiber length was too weak to excite the orthogonal polarization mode which generally exists in longer FFP lasers, and single-polarization lasing was sustained for all pump and tuning ranges. This laser was extremely sensitive to cavity alignment, and an index-matching fluid was required to obtain a continuous wavelength-tuning over 1.45nm, as shown with 4 sample wavelengths in Fig.3(b), which corresponds to only 26% of the resonator's FSR. It was evident that the gap-induced intra-cavity loss is mainly responsible for limiting the tuning range. Fig.4(a) is the resulting optical spectrum obtained using a FFP scanning interferometer (FFP-SI) and has a FSR=3.3GHz and a bandwidth (BW)=26MHz, illustrating single-mode and single-polarization operation. Fig.4(b) shows the lasing profile obtained using another FFP-SI, which is resolution-limited at 2.8MHz.

In order to obtain single-mode lasing with longer lengths (which enable higher pump absorption, and hence higher output powers) an alternative 3-mirror compound-cavity configuration was investigated (Fig.1(b)). Theoretically, single-frequency and discrete wavelength-tuning operation is possible with a longer active section l_1 by fine adjustments of the secondary cavity l_2, which consists of a passive section and an air-gap. Furthermore, the discrete wavelength spacing corresponds to FSR_1 of the active cavity, while the total tuning range corresponds to FSR_2 of the passive filter section. Table 2 lists parameters of the various compound-cavity FFP laser that have been attempted to date, and their corresponding tuning ranges. Note that l_2 values in Table 2 include zero air-gap distance, and the air-gap only increases by ~1um to 2um upon tuning.

Table 2: Compound-cavity FFP laser performance (l_2 assumes air-gap=0.0mm)

#	R1(%)	l_1(mm)	R2(%)	l_2(um)	R3(%)	$D\lambda$ (nm)
(a)	99.9	0.99	97.5	**100**	99	4.03
(b)	99.9	0.99	97.5	**80**	99	4.81
(c)	99.9	10.5	92	**186**	92	1.24
(d)	99.9	10.5	92	**115**	92	5.45
(e)	99.9	9.25	68	**502**	99	0.42
(f)	99.9	9.25	68	**325**	99	1.6

Laser(a) without R3 did not lase due to low R2; but with R3 coupled, 5 discrete single-frequencies were achieved over a 4.03nm span as shown in Fig.5(a). With l_2 reduced to 80um (laser(b)), 7 frequencies were obtained over a range of 4.81nm, as shown in Fig.5(b), but the output power only reached ~10uW. To increase output powers, subsequent experiments used longer cavities (~10mm). Laser(c) supported lasing in the first cavity, and single-frequency tuning was achieved over only 1.24nm. With l_2 reduced to 115um in laser(d), the resulting filter BW was insufficient to select a single frequency; consequently there was a weak side-mode (spaced by FSR$_1$) associated with a main mode. These two modes could be tuned over 5.45nm, as shown in Fig.5(c), and the output power reached 0.5mW (limited by detector saturation). In an effort to increase coupling between the two cavities, a lower R2 was used in laser(e). However, due to a small FSR$_2$, single-frequency tuning was achieved only at 6 positions over a 0.42nm range, as shown in Fig.5(d), without exciting another mode spaced by FSR$_2$. In laser(f) a shorter l_2 gave a wider FSR$_2$, as well as a broader filter BW, therefore exciting one mode group consisting of one dominant mode and a weak side-mode spaced by FSR$_1$, and discrete tuning was achieved over 1.6nm. The above experiments illustrated that discrete single-frequency tuning can be achieved by laser(b) over a range much greater than that achievable by a single-cavity laser of 1mm length (which has a FSR=0.8nm). Thus longer compound-cavity lasers have shown potential for wide tuning ranges with higher output powers than those affordable by ultrashort-cavity FFP lasers. Optimized compound-cavity FFP laser designs must be carried out to fully exploit their potential advantages. These designs and their characteristics will be presented at the conference.

Conclusion We have demonstrated, for the first time, single-frequency lasing in ultrashort cavity Er:Yb P-Si FFP lasers with continuous wavelength-tuning. Compound-cavity FFP lasers have shown potentially broad discrete-wavelength tuning ranges and higher output powers than their ultrashort-cavity counterparts. These compact and miniature FFP lasers should provide good environmental stability and convenience for device packaging and thermal control. Their performance can be considerably improved by better fiber and mirror designs and this should improve the output power and tuning range of the FFP lasers.

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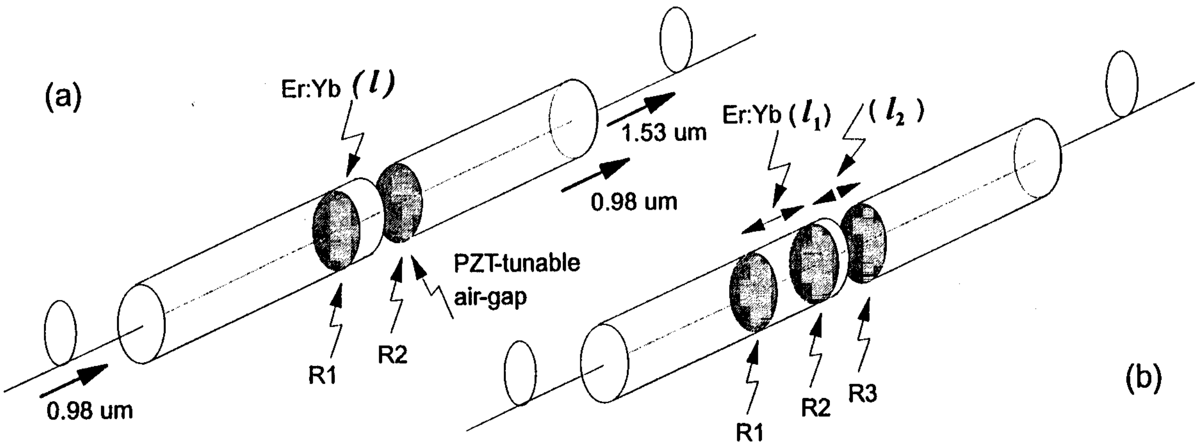

Fig.1 (a) Single-cavity, and (b) compound-cavity Er:Yb P-Si FFP laser configurations.

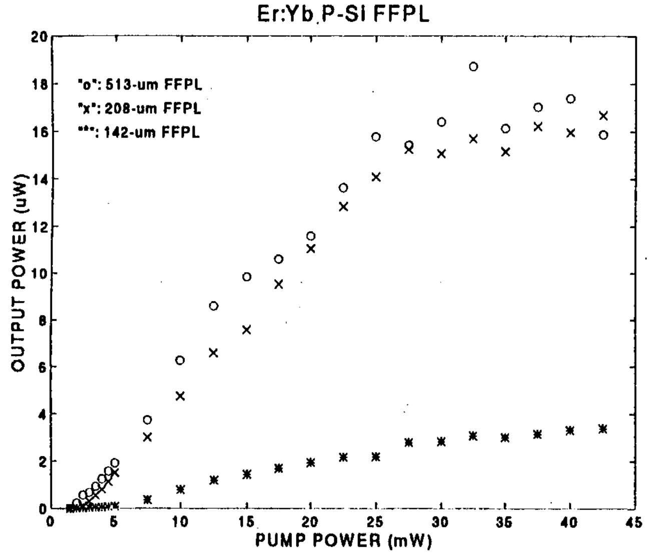

Fig.2 Laser output power versus input pump power of the 513um, 208um, and 142um Er:Yb P-Si FFP lasers.

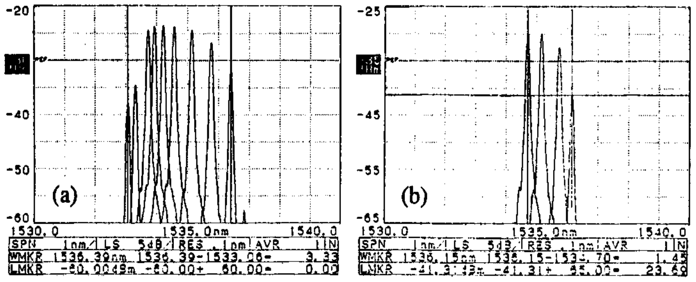

Fig.3 Tuning ranges of the (a) 208um, and (b) 142um, Er:Yb P-Si FFP lasers

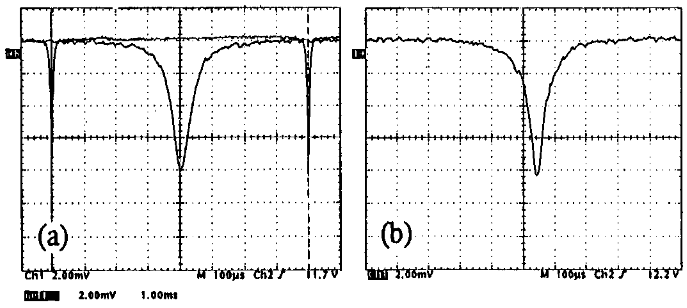

Fig.4 Optical spectra of the 142um laser at 32mW pump level observed by (a) a FFP-SI of FSR=3.3GHz, BW=26MHz. Note the expanded lasing profile at the center is superimposed onto the FSR of the FFP-SI; (b) a FFP-SI of FSR=357MHz, BW=2.8MHz.

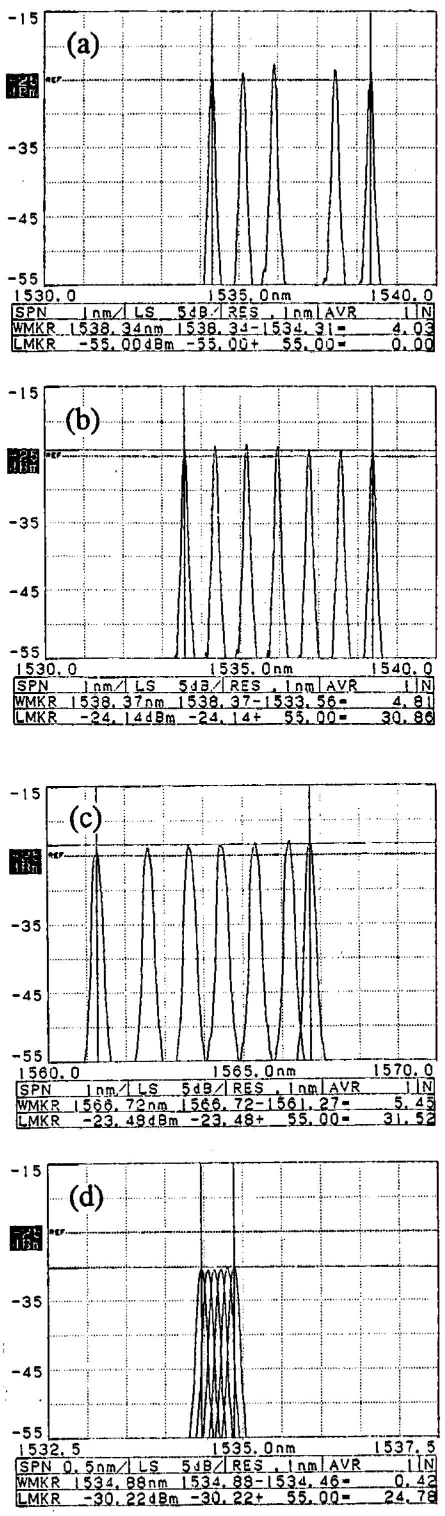

Fig.5 Discrete wavelength tuning ranges obtained from compound-cavity Er:Yb P-Si FFP lasers designated in Table 2: (a) laser(a), (b) laser(b), (c) laser(d), and (d) laser(e).