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Single-Mode Tunable Erbium:Ytterbium Phosphate Fiber Fabry-Perot Laser

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Abstract

A compact tunable single-mode fiber laser is developed by using a novel combination of high-gain erbium:ytterbium (Er:Yb) phosphate fiber and fiber Fabry-Perot (FFP) cavity configurations. Experiments demonstrate the shortest Er:Yb phosphate FFP laser ever reported, which has a 100-um cavity length with a continuous wavelength tuning range over 4.52 nm, as limited by the sharp fiber gain peak. In addition, an alternative 3-mirror laser design has also demonstrated single-mode lasing operation.

Erbium fiber lasers emitting in 1.55-um wavelength region have been under intensive research for applications in telecommunications, spectroscopy, and fiber sensors. Single-mode fiber lasers constructed with either Fabry-Perot cavities or ring cavities usually require certain 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. Recently a microchip erbium:ytterbium (Er:Yb) phosphate glass laser has achieved single-mode operation in a 200-um Fabry-Perot cavity without additional filtering [5]. Here we report a compact tunable single-mode fiber laser using a novel combination of Er:Yb phosphate fiber and fiber Fabry-Perot (FFP) cavity configurations. The attractive features of Er:Yb phosphate glass are its broad absorption band, efficient pump absorption, and large stimulated emission cross-section. The FFP technology allows fabrication of very short cavities (> 10 um) and continuous wavelength tunability with low loss [6]. Single longitudinal-mode operation can be obtained when the mode spacing of a short cavity is large relative to the gain bandwidth such that only one mode acquires sufficient gain to reach lasing threshold. Continuous wavelength-tuning can be achieved by piezoelectric tuning of the FFP cavity length. The experimental work demonstrates the shortest Er:Yb phosphate FFP laser ever reported, which has a 100-um cavity length with a continuous wavelength tuning range over 4.52 nm, as limited by the sharp gain peak. In addition to the simple 2-mirror cavity design, single-mode operation is also obtained in a longer active cavity using a 3-mirror cavity configuration.

The experimental setup is shown in Fig.1(a), while the 2-mirror FFP laser with length l and the 3-mirror FFP cavity with lengths l_1 and l_2 are sketched in Fig.1(b) and (c) respectively. The laser cavity is mounted in a piezoelectric transducer (PZT) stage capable of air-gap tuning.

Lasing output was monitored by several FFP scanning interferometers (FFP-SIs) with different free spectral ranges (FSRs) and bandwidths (BWs). The phosphate fiber has Er:Yb dopings of 1600:38000 ppm respectively, and a cut-off near 1060 nm which can support higher order transverse modes at 980 nm.

Laser cavity lengths (*l*) investigated range from 1 mm to 55 um. Single-mode lasing can be obtained for l=500 um with R1=99.9% and R2=99.0%, and for l<200 um with R1=R2=99.9%. The minimum cavity length calculated for present laser structure is ~50 um assuming no cavity loss; however, the shortest successful length investigated is 100 um, and the next cavity length of 55 um failed to lase. At most cavity coupling positions an auxiliary mode often exists that, depending on cavity lengths, may correspond to a narrow spacing in tens to hundreds of MHz. This is suspected to be the polarization mode due to phosphate fiber birefringence and mirror anisotropy. Even initially single-mode, this polarization mode may arise at higher pump levels and tuning voltages; consequently, main-mode lasing is ensured while a polarization mode may arise during operations. Fig.2 shows the output versus input pump power (P_p) of the 100-um laser operating at a stable single-mode, giving a pump threshold ~1.5 mW, a maximum output ~21 uW, and a slope efficiency (SE) ~0.06% before saturation at P_p~30 mW. Continuous wavelength-tuning over 4.52 nm (~574 GHz, from 1531.72 to 1536.24 nm) without mode-hopping is obtained with a tuning voltage from 0 V to 14.3 V, and Fig.3 shows the wavelengths displayed at 9 discrete voltages. For comparison, the experimental tuning range as a fraction of FSR of the 199, 158, and 100-um cavities are respectively 77%, 76%, and 59%; therefore the tuning range is possibly limited by the sharp gain peak. Figs.4(a) and (b) show the optical spectra at P_p=18 mW obtained respectively from a FFP-SI of

FSR=3.3GHz/BW=26MHz and a FFP-SI of FSR=357MHz/BW=2.8MHz. The spectral profile in Fig.4(b) appears noisy and gives a direct optical linewidth of ~2.8 MHz. This linewidth is limited partly due to the intrinsic relaxation oscillation, noisy pump laser, and multiple transverse pump modes. Relaxation oscillation frequencies (f_r) were measured indirectly using the oscilloscope's Fast Fourier Transform, giving a $f_r \sim 940$ KHz (as shown in Fig.5) and 1.4 MHz at $P_p \sim 18$ and 43 mW respectively. Note that Fig.5 also displays the DC level of the output power with a relaxation oscillation depth <2%. Another interesting observation revealed that during single-mode lasing, the output polarization may change at certain tuning voltages. This effect can be observed using a polarization-sensitive FFP-SI, where a change in the lasing polarization state is manifested by the emergence of a resonance doublet in the FFP-SI. When the WDM's backward output is terminated by a mirror (R=99.4%), the forward laser output nearly doubles to a SE~0.12% for $P_p < 30$ mW as shown in Fig.2; however, the linewidth is still limited by a high relaxation oscillation frequency of ~550 KHz at $P_p \sim 18$ mW. Moreover, there is also a continuous hopping between two modes spaced ~35 MHz as excited by the external cavity.

An alternative laser design investigated is a 3-mirror cavity configuration shown in Fig.1(c). Theoretically, single-mode and discrete wavelength-tuning operation is possible with a longer active l_1 section by fine adjustments of the l_2 cavity air-gap. The preliminary study employed a device structure of an active l_1=0.737 mm and a passive l_2=65.3 um (air-gap=0.0 mm), and R1=99.9%, R2=R3=99.0%. There are typically 2-4 modes spaced by ~135 GHz in the lasing spectrum of the single 0.737-mm cavity. With R3 coupled, the output still emits multimode spectrum near threshold; but at higher P_p (~15 mW in this case) single main-mode is established with zero tuning voltage, and a polarization mode also appears at higher pump levels with a spacing of ~566 MHz. A typical output versus P_p curve in Fig.6 shows a 1.5-mW pump threshold and a SE ~ 0.15% for Pp < 30 mW, and that the kinks are not associated with any mode-hopping. This laser showed poor wavelength tuning capability, and in general its spectrum varies between single-mode and multimode as a function of tuning voltage.

In conclusion, initial experiments have demonstrated the feasibility of very short cavity Er:Yb phosphate FFP lasers capable of continuous wavelength-tuning. Their miniature dimensions should provide good environmental stability and convenience for device packaging and thermal control. It is expected that better phosphate fiber and mirror designs should improve FFP lasers' output power, linewidth, and tuning range. Interesting characteristics are also observed in the 3-mirror FFP laser which warrants a proper design using detailed theoretical modelling.

Reference

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Figure Caption

Fig.1 (a) Experimental set-up, FFPC: fiber Fabry-Perot controller, PD: photodetector, OSA: optical spectrum analyzer; (b) 2-mirror and (c) 3-mirror Er:Yb phosphate FFP laser configurations.

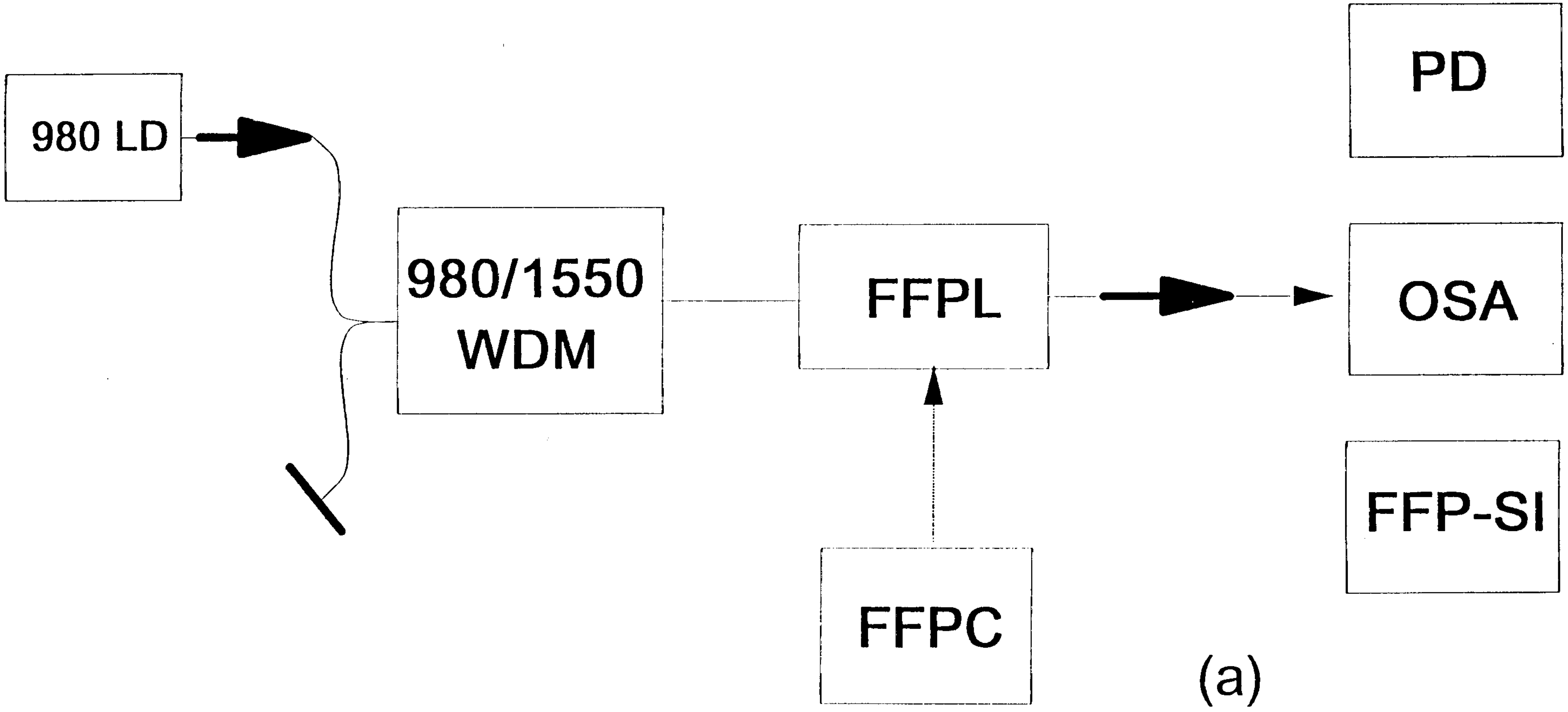
Fig.2 Laser output power versus input pump power of the 100-um Er:Yb phosphate FFP laser, with and without external optical feedback.

Fig.3 4.52-nm tuning range of the 100-um Er:Yb phosphate FFP laser; wavelengths displayed at 9 voltages.

Fig.4 Optical spectra of the 100-um Er:Yb phosphate FFP laser at 18 mW pump level observed by (a) FFP-SI of FSR=3.3GHz/BW=26MHz, and (b) FFP-SI of FSR=357 MHz/BW=2.8 MHz.

Fig.5 FFP laser output at 18 mW pump level and its Fast Fourier Transform (FFT) spectrum showing the relaxation oscillation peak near 940 KHz.

Fig.6 Laser output power versus input pump power of the 3-mirror Er:Yb phosphate FFP laser.



(a)

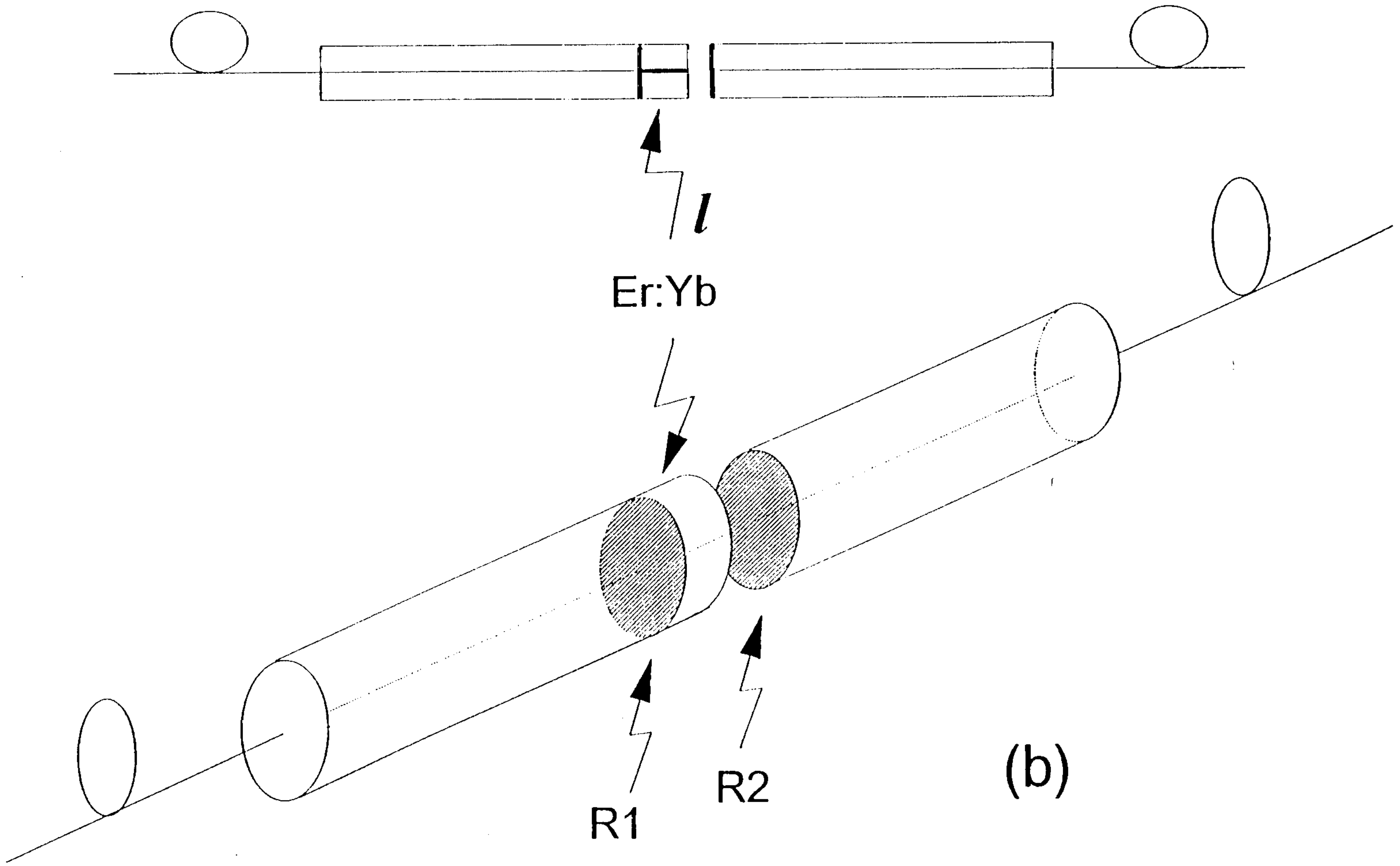
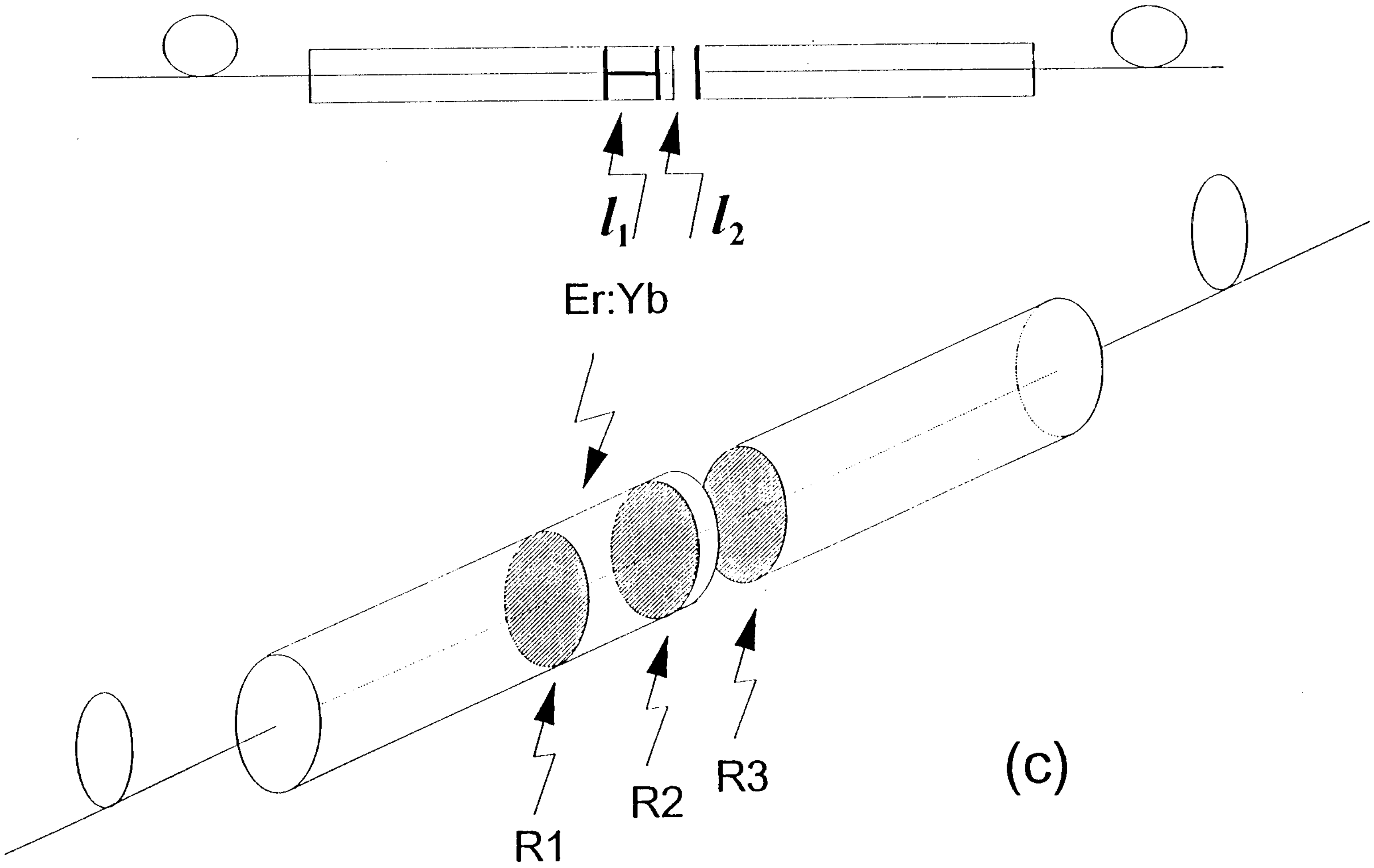
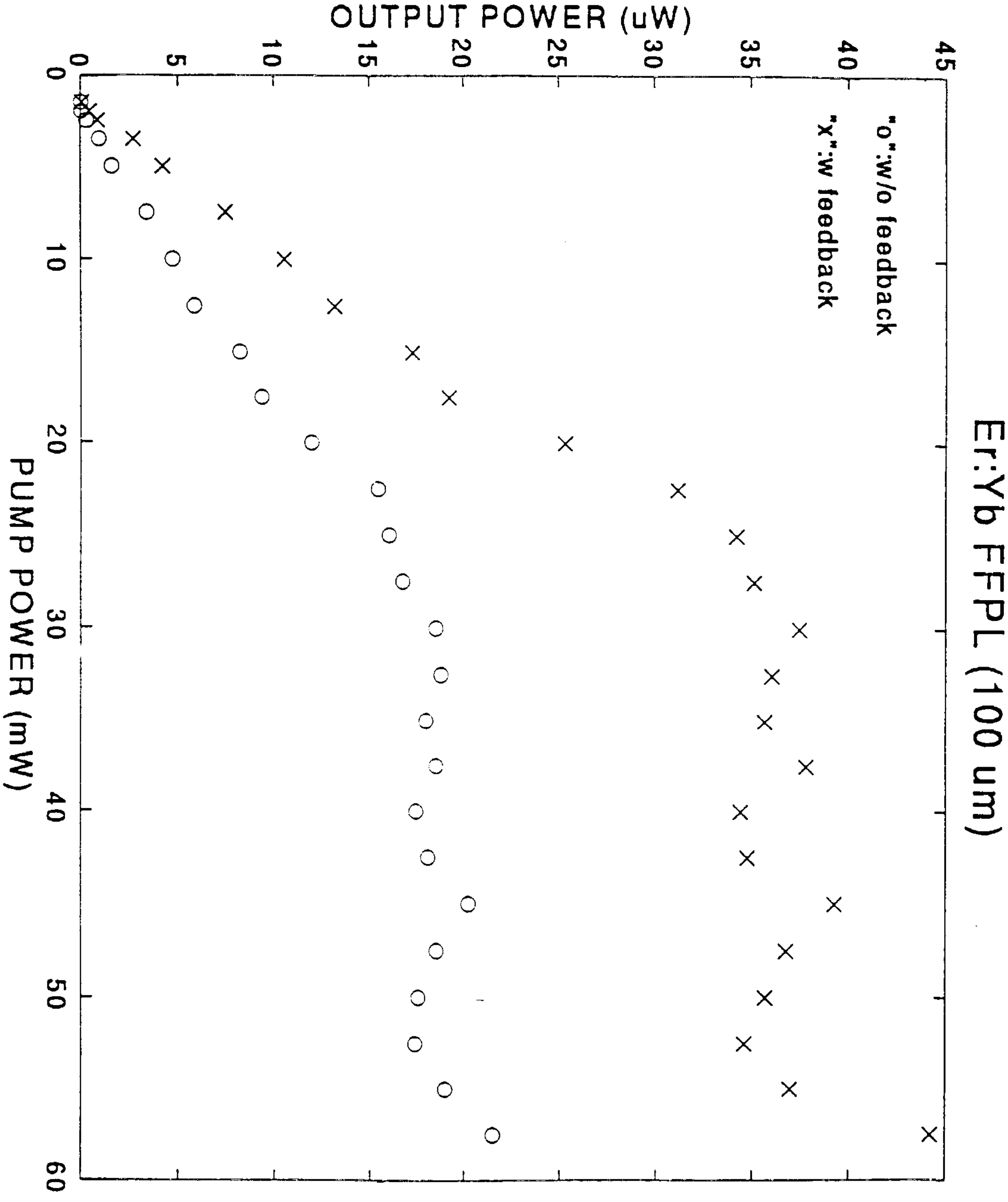


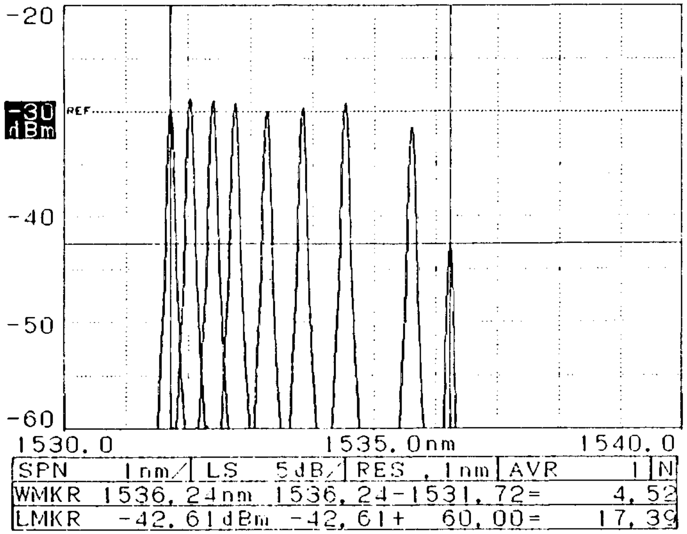
Fig 1



(c)

Fig 2


Er:Yb FFPL (100 um)
"o":w/o feedback
"x":w feedback
OUTPUT POWER (uW)
0
5
10
15
20
25
30
35
40
45
PUMP POWER (mW)
0
10
20
30
40
50
60



```
SPN     1nm/ | LS    5dB/ | RES  .1nm | AVR       1 | N
WMKR 1536.24nm 1536.24-1531.72=       4.52
LMKR   -42.61dBm -42.61+   60.00=     17.39
```

Fig 2

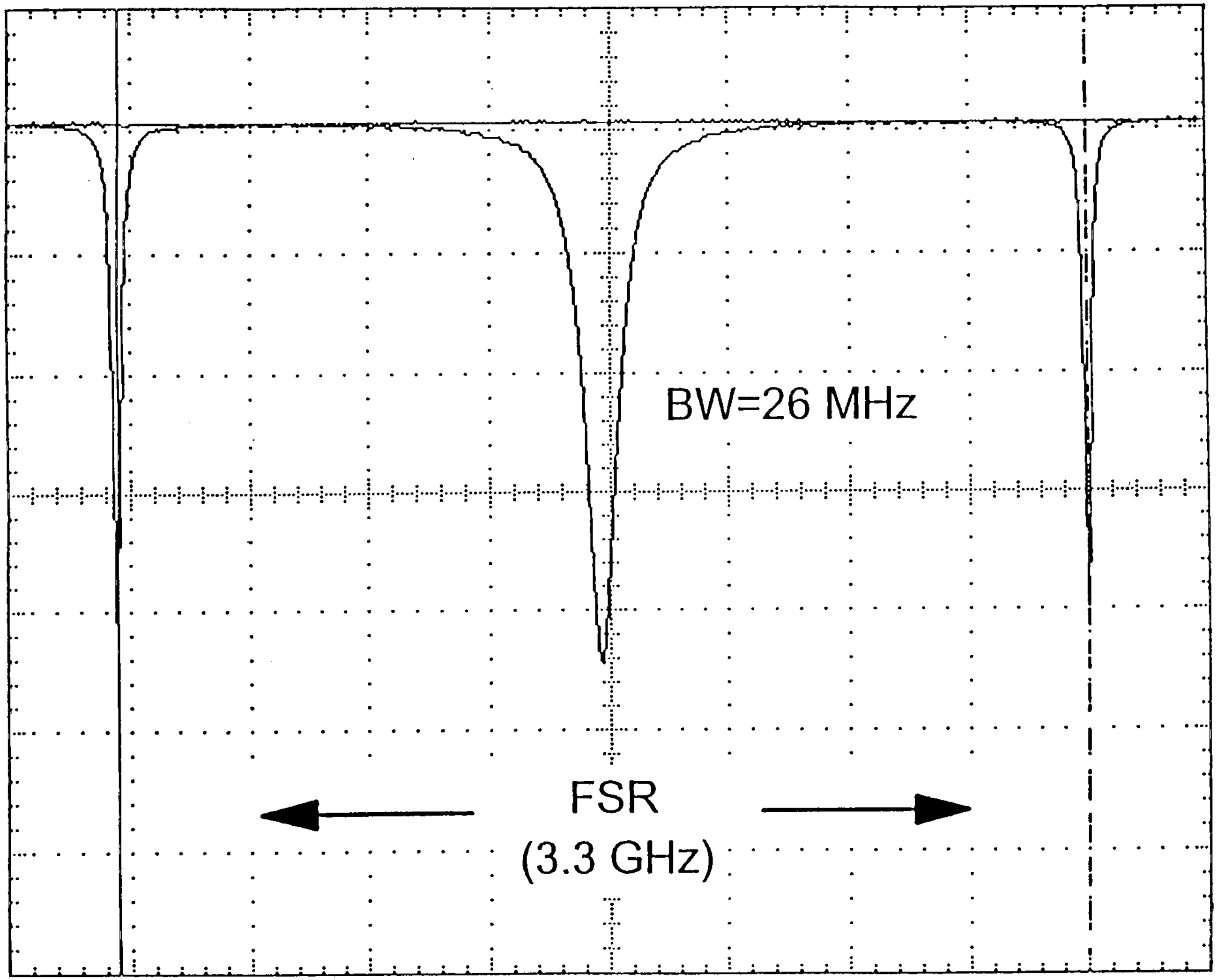


Fig. 7(a)

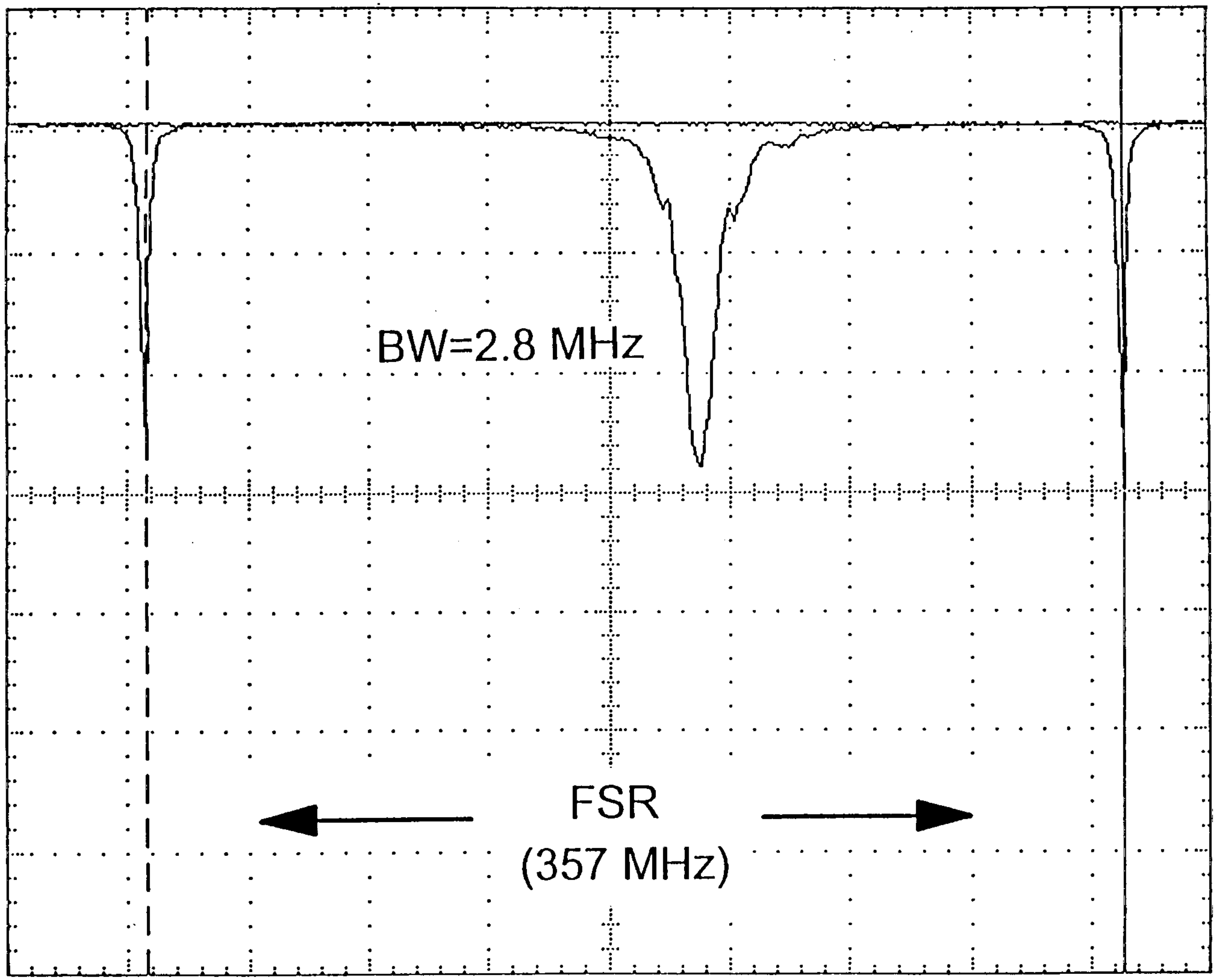


Fig 4(a)

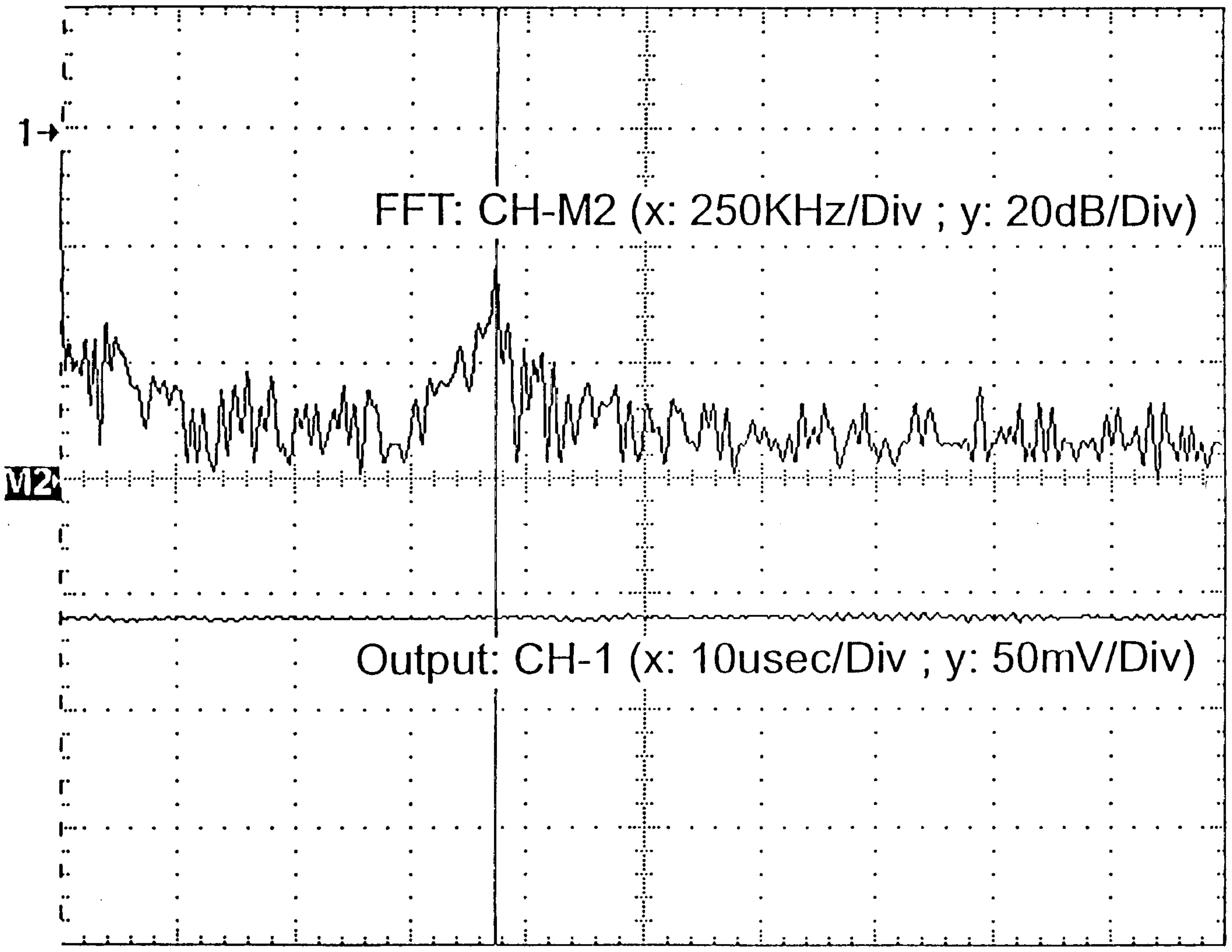

1→
FFT: CH-M2 (x: 250KHz/Div ; y: 20dB/Div)
M2
Output: CH-1 (x: 10usec/Div ; y: 50mV/Div)

Fig. 5

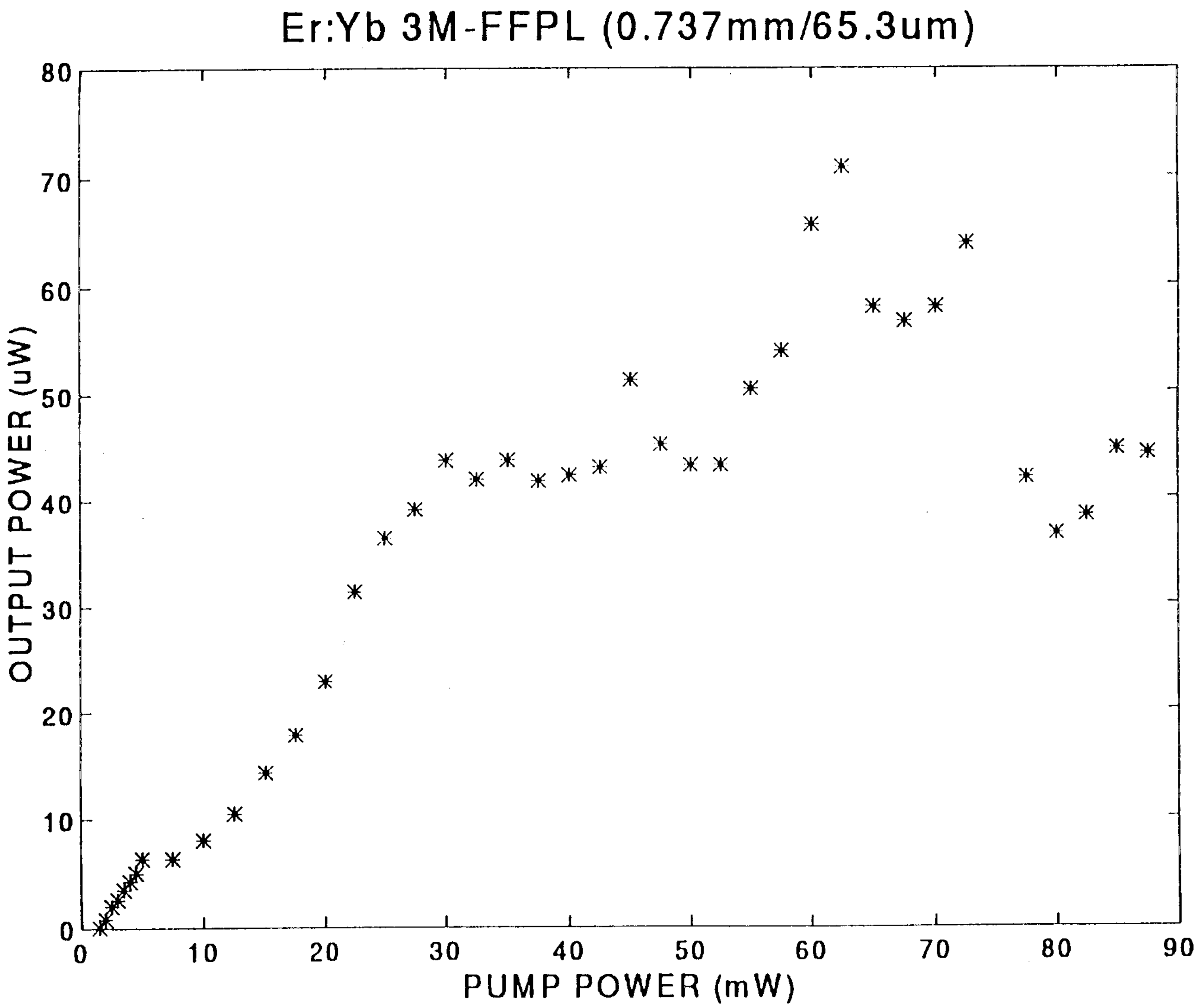

Er:Yb 3M-FFPL (0.737mm/65.3um)
OUTPUT POWER (uW)
0
10
20
30
40
50
60
70
80
PUMP POWER (mW)
0
10
20
30
40
50
60
70
80
90

Fig. 6