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Single-Frequency Travelling-Wave Erbium-Doped Fibre Loop Laser

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Abstract: *We report a novel erbium-doped fibre laser cavity configuration which produces single-longitudinal-mode operation with less than 10kHz linewidth. The fibre laser operates in a travelling-wave mode which prevents spatial holeburning from occurring. A principal advantage of the configuration is that it allows the precise and stable setting of the lasing wavelength.*

Introduction: Single-longitudinal-mode lasers operating in the 1.5μm region are important devices for use in future coherent optical communication systems and sensors. Single-frequency erbium-doped fibre lasers have been demonstrated using several schemes,[1,2,3,4] including travelling-wave operation. Travelling-wave operation eliminates spatial hole-burning in the gain medium and prevents multimode operation. We report here a new travelling-wave fibre laser configuration which allows the incorporation of a frequency-selective reflector in the cavity, thus permitting very precise control over the operating wavelength.

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The resonator configuration is illustrated in Figure 1, and is based on a single four-port coupler, with two of the ports joined in a Sagnac-like arrangement by a length of erbium-doped fibre. The operation of the loop is different from a Sagnac loop because an optical isolator is included to ensure uni-directional operation. The remaining two coupler ports are used to introduce the pump light and to incorporate a reflector to form a resonant cavity.

Experiment: The fibre loop was formed by joining two output ports of a 1.55μm 3dB coupler by a length of Er^{3+}-doped fibre (Er^{3+}conc.=800ppm, λ_c=1525nm, NA=0.15) and a pigtailed, polarisation-independent isolator. The isolator provided isolation of 45.2dB with insertion loss <0.4dB, return loss >60dB and polarisation sensitivity 0.02dB. Pump light was introduced through input port A, which was angle polished to prevent reflections. The standard telecommunications coupler had the favourable characteristic of coupling virtually all of the pump light into the section of doped fibre. A reflector, either in the form of a dielectric mirror (70% reflectivity) or a distributed Bragg reflector (DBR), was introduced to port B to complete the laser cavity. The DBR had a reflectivity of 70% and a bandwidth of 0.3nm centred at 1.552μm. It was fabricated by polishing a fibre mounted in a flat silica V-groove, holographically exposing a grating in photoresist on the polished surface and etching the grating into the fibre[5]. A polarisation controller was used in the loop because of the polarisation sensitivity of the DBR. The round-trip laser cavity length was 9.5m, corresponding to a passive cavity mode spacing of 21MHz. For convenience the laser was pumped at 980nm from a Ti:sapphire laser.

By virtue of the isolator and the location of the doped fibre *within* the fibre loop, the signal in the 1.55μm region generated by the Er^{3+}-doped fibre travels uni-directionally in the fibre loop, thus eliminating spatial hole-burning in the gain medium. The coupler acts as the output coupler of the laser and sends half of the signal to the reflector on port B. Half of the signal returned from the reflector is fed back into the active fibre. Operation is similar to the travelling-wave fibre ring laser previously demonstrated[2], but because this laser cavity incorporates a reflector, it combines travelling-wave operation with the significant advantage of allowing the use of a frequency-selective reflector, thereby allowing very accurate wavelength selection.

In order to confirm the travelling-wave and single-longitudinal-mode operation, the laser was first operated with the dielectric mirror reflector on port B. Single-longitudinal-mode operation was observed at a wavelength of 1.5577μm. Single-frequency operation was verified by using a monochromator with 0.1nm resolution and a scanning Fabry-Perot spectrum analyser with free spectral range 1.3GHz and finesse >100. As additional proof of single-longitudinal-mode operation, no intermodal beat signal was detectable on an RF spectrum analyser.

With a mirror reflector, the laser configuration offers no significant advantage over the travelling-wave ring technique[2]. The advantage lies in the ability to accurately determine the operating wavelength by the use of a frequency-selective reflector, as demonstrated when the mirror on port B was replaced with the DBR with maximum reflectivity at 1.552μm, when the wavelength of operation shifted to 1.552μm, as illustrated by the monochromator spectrum illustrated in Figure 2. Again, only one mode was evident on the scanning Fabry-Perot spectrum analyser (Fig. 2), whose free spectral range was sufficient to resolve adjacent modes spaced 21MHz away. Moreover, no intermodal beat signal was observable.

The linewidth of the laser was determined by the delayed self-heterodyne technique, using a 25km delay line. The RF spectrum illustrated in Figure 3 corresponds to a spectral width of about 9.5kHz, fully resolvable by a 25km delay line. Variation of the laser linewidth with power was not significant, implying that the linewidth may be determined by the stability of the laser cavity to temperature effects and vibrations. Indeed, the measured linewidth was far larger than would be expected from the Schawlow-Townes limit (~1Hz).

Discussion: The laser power characteristic was determined for the signal output from port A and is illustrated in Figure 4. Threshold was measured to be 6mW launched pump power at 980nm, with a slope efficiency of 29%. Given the loss associated with the isolator and coupler, this slope efficiency represents a quantum efficiency of at least 95%. Because of the presence of the 3dB coupler in the cavity, the laser is inherently lossy, although the 50/50 splitting ratio is optimal for minimum threshold operation. Nonetheless, since the output coupling is large and is taken from the position in the cavity where the field is highest, high slope efficiency is possible, with 10mW output obtained for a pump power of 40mW. For a coupler splitting ratio $\alpha : 1 - \alpha$, the laser slope efficiency is proportional to α, while the gain required to achieve threshold is inversely proportional to $\alpha(1 - \alpha)$. Higher slope efficiency could be achieved with a different coupler splitting ratio, but would be at the expense of a higher threshold.

No attempt was made to isolate the laser cavity from temperature and acoustic disturbances and some mode-hopping was observed. This was particularly noticeable when the mirror reflector was used to complete the laser resonator. In this configuration the operating wavelength is determined by the gain curve of the Er^{3+}-doped fibre, which is relatively flat in the 1.55μm region, making the laser susceptible to mode-hopping when disturbed. Introducing the grating reflector not only allowed the wavelength to be accurately determined, but also considerably reduced the susceptibility to mode-hopping because of the sharp band-pass response of the resulting laser cavity. It is expected that improvements in stability will be achieved by stabilising the fibre loop and reducing the loop length to increase the passive-cavity mode-spacing.

Conclusions: We have demonstrated a novel fibre laser configuration which operates as a single longitudinal-mode device. The laser operates as a travelling-wave device and provides the ability to accurately determine the wavelength of operation. A linewidth of less than 10kHz has been demonstrated, with 6mW threshold and 29% slope efficiency.

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Figure Captions:

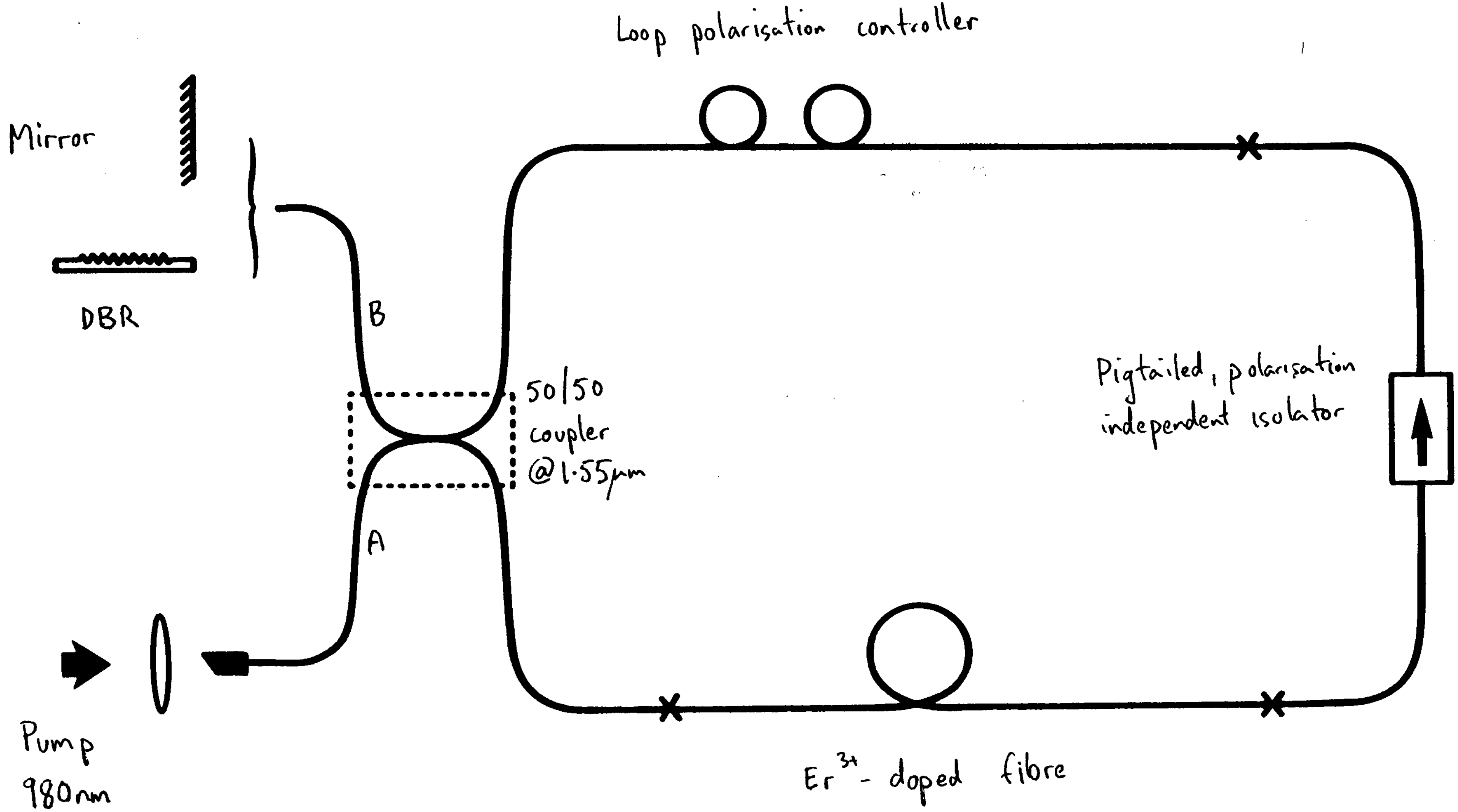
1. Erbium-doped fibre loop laser experimental configuration.

2. Fibre laser output spectrum measured by monochromator with 0.1nm resolution (inset) and by scanning Fabry-Perot interferometer

3. Spectral linewidth determined by delayed self-heterodyne technique with 25km delay line.

4. Fibre laser output power characteristics a function of 980nm pump power

Figure 1



Loop polarisation controller
Mirror
DBR
B
50/50
coupler
@1·55μm
A
Pump
980nm
Pigtailed, polarisation
independent isolator
Er3+ - doped fibre

Figure 2

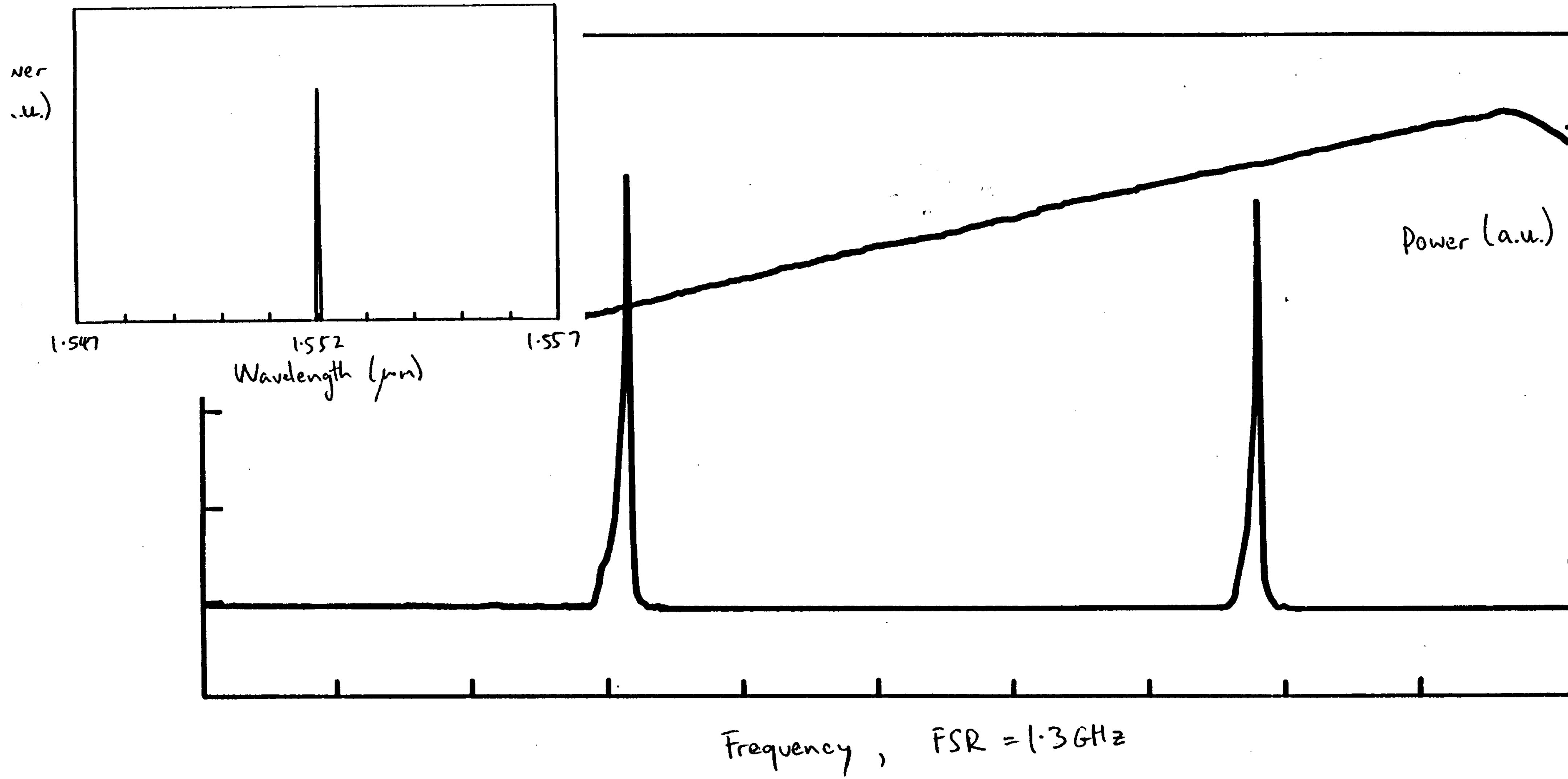

wer
.u.)
1·547
1·552
1·557
Wavelength (μm)
Power (a.u.)
Frequency , FSR = 1·3GHz

Figure 3

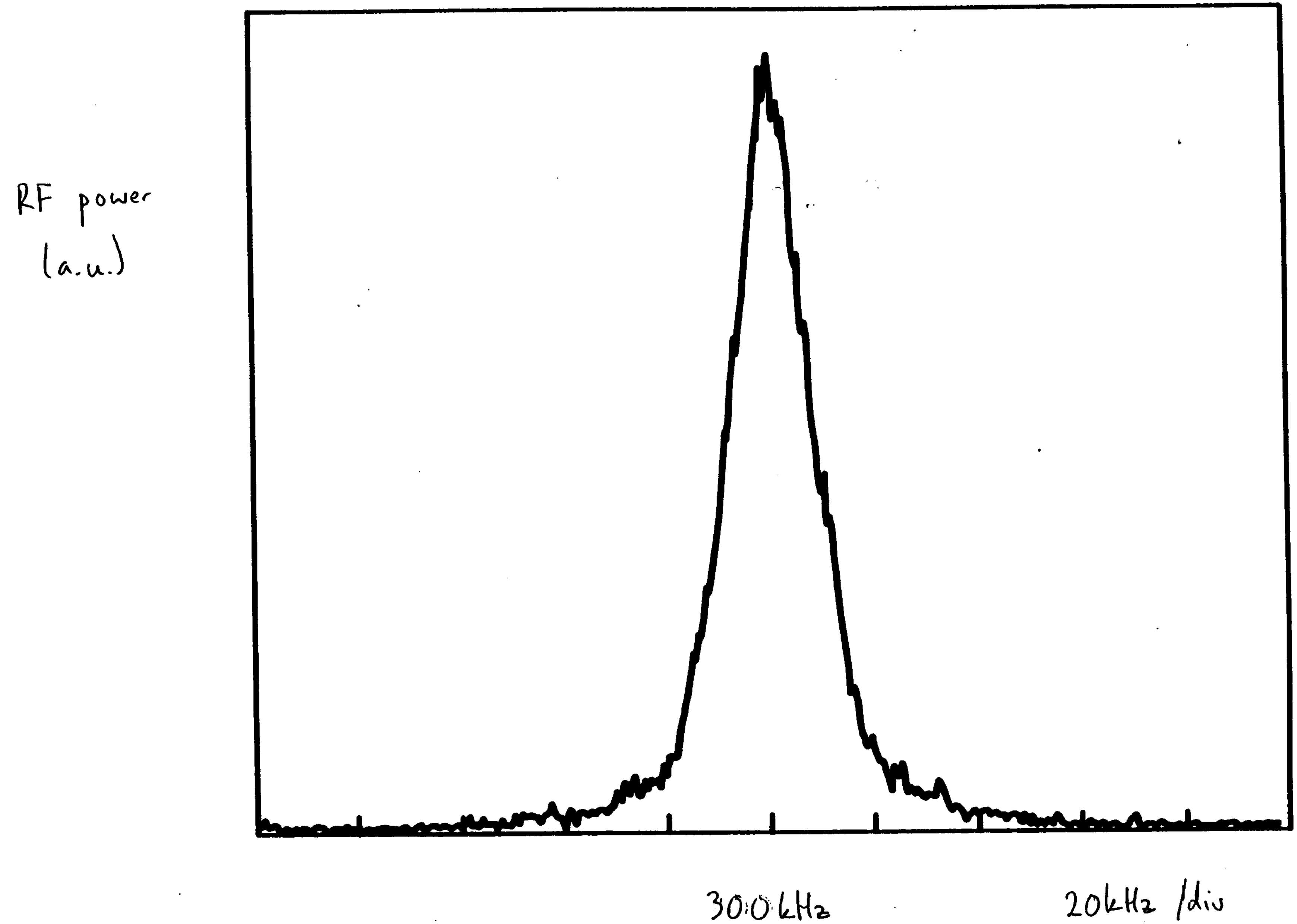
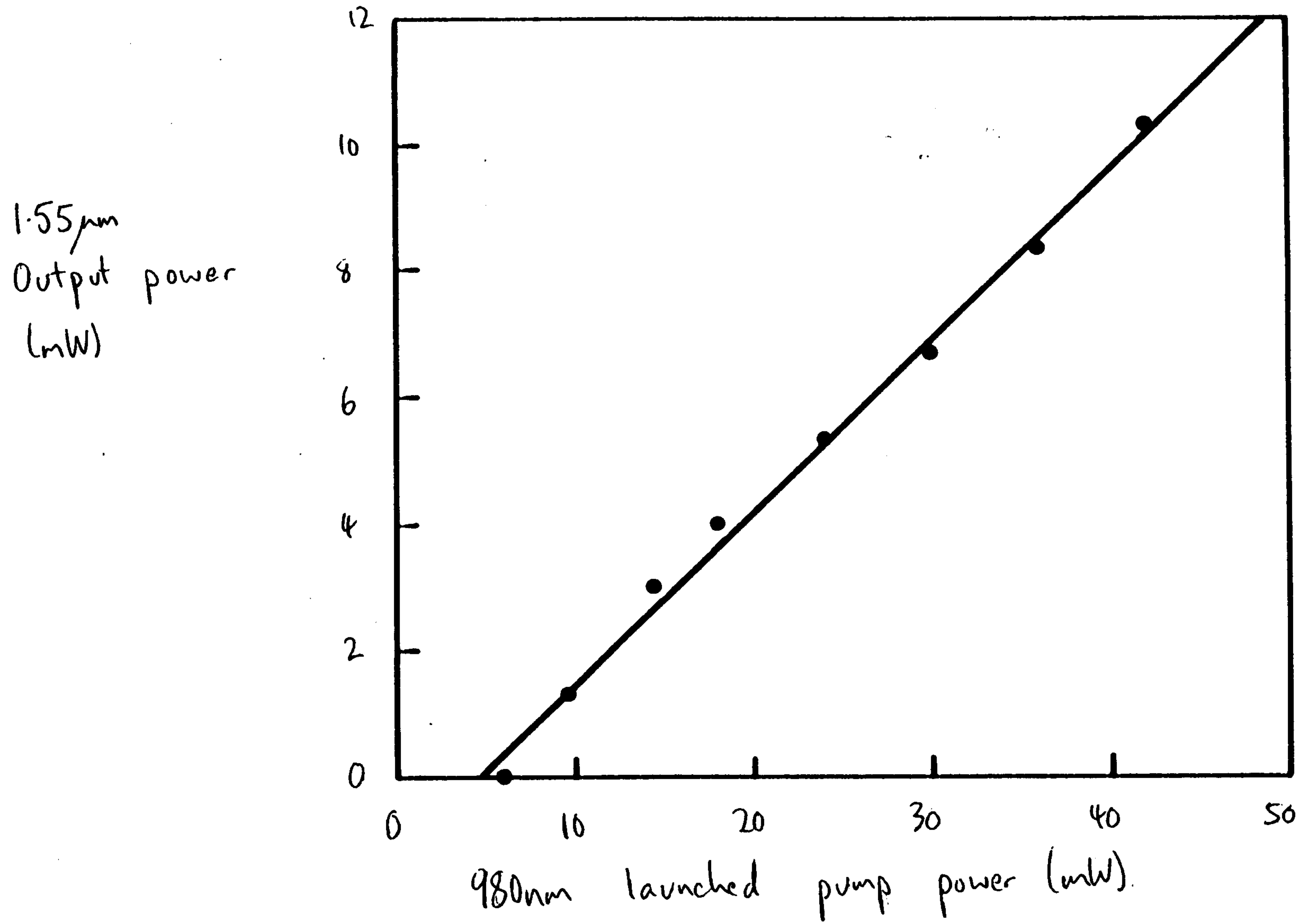


Figure 4


1.55μm
Output power
(mW)
12
10
8
6
4
2
0
0
10
20
30
40
50
980nm launched pump power (mW)