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STABLE SINGLE-FREQUENCY TRAVELLING-WAVE FIBER LOOP LASER WITH INTEGRAL SATURABLE ABSORBER BASED TRACKING NARROWBAND FILTER

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ABSTRACT

We demonstrate stable single-frequency and polarization operation of a travelling-wave Er^{3+}:Yb^{3+}-doped fiber loop laser by incorporating an unpumped Er^{3+}-doped fiber section butted against a narrowband feedback reflector. The saturable absorber acts as a narrow bandpass filter which automatically tracks the lasing wavelength, thus ensuring single-frequency operation. Output powers up to 6.2 mW at 1535 nm were obtained for launched pump powers of 175 mW at 1064 nm. At this output, the RIN was less than -112 dB/Hz at frequencies above 200 kHz and the laser linewidth less than 0.95 kHz whilst the lasing frequency was observed to drift slowly ($\sim$ 170 MHz/hr) due to environmental effects.

Narrow-linewidth single-frequency fiber lasers are of great importance in many applications, such as wavelength division multiplexing and coherent communications. Single frequency operation in Fabry-Perot type lasers can be obtained either by making the cavity extremely short (<1 mm) [1] or by combining a short length (~ 5 cm) with fiber-grating feedback for mode-suppression and wavelength selection [2]. Recently the use of fiber-grating feedback has also enabled the first demonstration of a single-mode fiber DFB laser [3]. As a result of their inherent short length these lasers normally suffer from a low pump absorption and hence low slope efficiency. In short Er^{3+}-doped fiber lasers, this problem can be alleviated by co-doping with Yb^{3+} [4]. More importantly, they suffer from a limited (<5 nm) tunability. Alternatively single-frequency operation can be obtained using travelling-wave ring [5,6] and loop [7] cavities. These have potentially high slope efficiencies, and most importantly they can be made widely tunable (>30 nm). Owing to the long cavity lengths, they also give narrow linewidth. Unfortunately, they are more complex and, because of their long cavities, susceptible to mode-hopping. To supress mode-hopping, bandpass filters (one narrow and one broad) [5,6], and active stabilization [8,9] were used. However, it has been shown that standing-wave saturation effects in Er^{3+}-doped fiber amplifiers can be employed to establish narrowband reflection filters [10] and more recently, an unpumped Er^{3+}-doped fiber was incorporated in a long Fabry-Perot laser cavity as a saturable absorber to establish linewidth narrowing and single mode operation [11].

In this paper, we show that a single-frequency fiber loop laser [7] can be effectively prevented from mode-hopping, and thus significantly improved in frequency stability, by the addition of an unpumped Er^{3+}-doped fiber at the standing-wave section. In this laser, the gain medium is incorporated within a loop along with an isolator to ensure travelling-wave operation of this section whilst feedback is provided to the loop by an unpumped Er^{3+}-doped fiber section butted against a high reflector. In our case this reflector was a narrowband fiber Bragg grating to provide coarse wavelength selection in the cavity. A self-written filter is produced due to standing-wave saturation effects in the unpumped Er^{3+}-doped fiber. The bandwidth of the filter mainly depends on the length of the saturable absorber whilst its strength is a function of the Er^{3+}concentration. The bandwidth of this filter is typically narrow (few tens of MHz), and its centre frequency tracks the lasing mode thus maintaining stable single frequency operation. In addition we believe that the absorber with appropriate linear birefringence and length acts as a polarizer since it has a preferred axis for efficient saturable absorption and thus ensures stable single polarization mode operation in the cavity.

A stable single frequency and polarization fiber loop laser is demonstrated with linewidth less than 0.95 kHz. The laser operates at 1535 nm with an output power of 6.2 mW and RIN of less than -112 dB/Hz at frequencies above 200 kHz. The laser frequency was observed to drift slowly by typically 170 MHz/hr as a result of small changes in the cavity length induced by environmental effects. This drift is an order of magnitude greater than the longitudinal mode-spacing of the cavity, but still did not induce mode-hopping, thus confirming the effectiveness of the tracking filter. Obviously, by stabilizing the cavity length, sub-MHz stability of the laser frequency should be possible.

The laser configuration, illustrated in Figure 1, is based on a four-port 80/20 fiber coupler. Two of the ports are joined in a loop by a 0.8 m length of Er^{3+}:Yb^{3+} co-doped fiber (1000 ppm Er^{3+}, 12500 ppm Yb^{3+}, NA = 0.22 and $\lambda_{cutoff} = 1150$ nm), a wavelength division multiplexing (WDM) coupler and an isolator. Up to 180 mW of pump power at 1064 nm was launched into the doped fiber. The isolator exhibited an extinction ratio of 45 dB and polarization sensitivity of 0.02 dB and thus ensured travelling-wave operation in the gain section. Given the unidirectionality of the light within the loop, output was taken from the remaining 80% coupler port whilst the 20% port was employed for feedback. Feedback was provided by an unpumped length of Er^{3+} doped fiber (length 0.2 - 6 m, NA = 0.2, λ_{cutoff} = 940 nm, and absorption of 4.3 dB/m @ 1535 nm) spliced to a 100% reflectivity fiber Bragg grating (λ_g= 1535 nm, $\Delta\lambda$ = 0.5 nm). This reflector was used as a coarse wavelength-selective element to establish a standing wave in the unpumped Er^{3+}-doped fiber and thus the narrowband tracking filter at 1535 nm. The total roundtrip cavity loss is estimated to be about 11.5 dB (excluding absorption loss in the unpumped Er^{3+}-doped fiber), with 7 dB from the 80% laser output, 3.5 dB from mode mismatches and splice losses, and 1 dB from the isolator and couplers. The total cavity length is about 13 m corresponding to a longitudinal mode-spacing of 15.8 MHz. To provide some isolation from environmental perturbations, the laser cavity was placed inside a styrofoam box.

Single frequency operation was investigated using a combination of an Ando AQ-6315A optical spectrum analyzer with a resolution of 0.05 nm, a Newport Supercavity scanning interferometer which has a free spectral range of 6 GHz and resolution of 1.2 MHz, and a 25 km delay-line interferometer.

Initially, 4 m of standard undoped single mode fiber (λ_c = 1250 nm, NA = 0.11) was used in the standing-wave section and then butted to a 100% mirror. Single mode operation at 1543 nm was observed around threshold. However, frequent mode-hopping was observed, on average every few seconds. The mode hopping takes place between neighbouring cavity modes (~16 MHz), and is most likely caused by small environmental fluctuations in the cavity length.

With the fiber replaced by a 4 m length of Er^{3+}-doped fiber, single mode operation with one single-polarized state at 1543 nm was observed for launched pump powers up to 83mW. The mode hopping was reduced and occurred on average every 3 minutes. However, unlike the previous case, when it occurred, the mode would hop to another several Å away. This is believed to be a result of an interplay between the spectrum of the gain and absorber sections which adjust slightly as the filter is written, to accommodate the reduction in cavity loss at the laser mode. If the absorbing filter is temporarily rendered ineffective due to a sudden (<10 ms) change in the laser cavity, as might be caused by vibrations, the laser will have to re-establish itself, most probably at a slightly different wavelength.

For a practical tunable laser, wavelength tuning would be provided by a coarse filter and stability against mode-hopping by the tracking filter. To demonstrate this, the mirror was replaced with a fiber Bragg grating reflector with a 5 Å bandwidth. The grating was centred at 1535 nm and had 100% reflectivity. To investigate mode-stability, several different lengths of saturable absorber between 1.5 and 6 m were used. The optimum length of saturable absorber which yielded the highest stable single frequency operation with high output was found be 4 meters, and stable single frequency operation was observed for periods in excess of 2 hours. In general, the laser output is elliptically-polarized, but a linearly-polarized output could be obtained by employing a polarization controller within the loop as well. Single polarization operation was confirmed by passing the output through a polarizer and analyzing with a detector and RF spectrum analyzer. No beat signal was observed.

The laser characteristics measured at port A with different lengths of saturable absorber are shown in Figure 2(b)-(f). The characteristics just above threshold are clearly nonlinear. In curve 2(b), a second threshold was observed when short lengths of saturable absorber were used. Two orthogonal polarization modes was found to operate above their second threshold. For curve 2(c), stable single-frequency and polarization operation was observed for pump powers up to 120 mW. For higher pump powers; two orthogonal polarization modes were again observed, where one polarization mode appears to be more stable than the other. In curves 2(e) and (f), stable single frequency and polarization operation was observed for extended periods (>2 hours), but the threshold is high due to the absorption loss. It is clear from these results that with appropriate length ($\geq$4 m) the saturable absorber can also suppress dual polarization as well as ensuring single-frequency operation of the laser.

For the optimum length of 4 m (curve 2(d)), the frequency jitter observed using the scanning Fabry-Perot interferometer was found to be ~6 MHz within 5 minutes and drift about 170 MHz in one hour. This frequency drift is significantly larger than the longitudinal mode-spacing of the cavity (16MHz) and illustrates the ability of the absorption filter to track the laser mode due to slow cavity length changes. To measure the linewidth a self-heterodyne setup with a delay line of 25km, giving a delay time of 120 μs was employed. The beat signal, detected by a photoreceiver and an RF spectrum analyzer, is shown in Figure 3. In this case the pump power was 175 mW and the laser output 6.2 mW. The observed linewidth of the spectrum is 0.95 kHz which corresponds to a coherence time of 328 μs. Since this is larger than the delay time, we can conclude that the optical linewidth of the laser is less than 0.95 kHz [12]. The Relative intensity noise (RIN) of the laser was measured using a low noise photoreceiver (Newfocus IR DC-1GHz) and RF spectrum analyser. Figure 4 shows the measured RIN in the frequency range 0 to 500 kHz. The RIN at the relaxation frequency of 65 kHz is about -77 dB/Hz, and was observed to decrease below -112 dB/Hz for frequencies above 200 kHz.

Finally, the Er^{3+}-doped fiber section was reduced to just 0.2 m, effectively eliminating the saturable absorption, and then spliced to the fiber Bragg grating. Single mode operation at 1535 nm was observed around threshold, however similar to the laser without the saturable absorber mode-hopping was observed on average every frew seconds, two orthogonal polarization modes were observed with different thresholds. The laser characteristic is now linear, as shown in Figure 2(a), with a slope efficiency of 5%, similar to those in the high power (>120mW pump) regime of the lasers (Figs. 2(b)-(f)), confirming that the saturable absorber mainly affects the laser threshold and not the slope efficiency.

In summary, stable single-frequency and polarization operation (> 2 hrs) of an Er^{3+}:Yb^{3+} co-doped fiber loop laser has been achieved by incorporating a narrowband tracking filter based on a standing-wave section of unpumped Er^{3+} doped fiber spliced to a narrowband fiber Bragg grating. Output powers up to 6.2 mW with a linewidth less than 0.95 kHz were measured whilst the laser exhibited a slow and controlled drift in laser frequency of ~ 170 MHz/hr. The technique offers the potential of a practical efficient tunable single frequency fiber laser. This could be achieved by replacing the fiber grating, which provides coarse wavelength selection, with a broadband reflector and incorporating a tunable element such as a bandpass filter within the loop. In addition any reduction of cavity losses would improve the slope efficiency and RIN.

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REFERENCES

1. K. HSU, C. M. MILLER, J. T. KRINGLEBOTN, E. M. TAYlOR, J. TOWNSEND, and D. N. PAYNE, Opt. Lett., **19**, 886 (1994).

2. I. M. JAUNCEY, J. E. REEKIE, J. E. TOWNSEND, D. N. PAYNE, and C. J. ROWE, Electron. Lett., **24**, 24 (1988).

3. J. T. KRINGLEBOTN, J.-L. ARCHAMBAULT, L. REEKIE, and D. N. PAYNE, Conf. on Lasers and Electro-Optics (CLEO-94), Anaheim, CA, May 1994, (paper CWP2), p. 261, and also submitted to Opt. Lett..

4. J. T. KRINGLEBOTN, P. R. MORKEL, L. REEKIE, J.-L. ARCHAMBAULT, and D. N. PAYNE, IEEE Photon. Technol. Lett., **5**, 1162 (1993).

5. N. PARK, J. W. DAWSON, and J. VAHALA, Appl.Phys. Lett., **59**, 2369 (1991).

6. J. L. ZYSKIND, J. W. SULHOFF, Y. SUN, J. STONE, L. W. STULZ, G. T. HARVEY, D. J. DIGIOVANNI, H. M. PRESBY, A. PICCIRILLI, U. KOREN, R. M. JOPSON, Electron. Lett., **27**, 2148 (1991).

7. G. J. COWLE, D. N. PAYNE, and D. REID, Electron. Lett., **27**, 229 (1991).

8. H. SABERT, and R. ULRICH, Opt. Lett., **8**, 878 (1993).

9. Y. C. YUE, G. W. SCHINN, J. W. Y. LIT, and J. ZHANG, Proc. Conf. on Optical Fiber Communications (OFC-94), pp. 129.

10. S. J. FRISKEN, Opt. Lett., **17**, 1776 (1992).

11. M. HOROWITZ, R. DAISY, B. FISCHER, and J. ZYSKIND, Electron. Lett., **30**, 648 (1994).

12. P. B. GALLION, and G. DEBARGE, IEEE J. Quantum Electron., **QE-20**, 343 (1984).

FIGURE CAPTIONS

Fig.1 : Fiber ring laser configuration.

Fig. 2: Lasing characteristics of single frequency fiber loop lasers with (a) 0.2 m; (b) 1.5 m; (c) 3 m; (d) 4 m; (e) 5 m and (f) 6 m of Er^{3+}-doped saturable absorbing fiber.

Fig. 3: Self-heterodyne measurement of laser linewidth using a 25 km delay line. The resolution bandwidth of RF spectrum analyzer is 300 Hz and sweep time is 10s. The measured linewidth is 0.95 kHz

Fig. 4: Relative intensity noise spectrum of the laser between 0 to 500 kHz. The resolution bandwidth is 3 kHz. . The relaxation oscillation frequency is at 65 kHz.

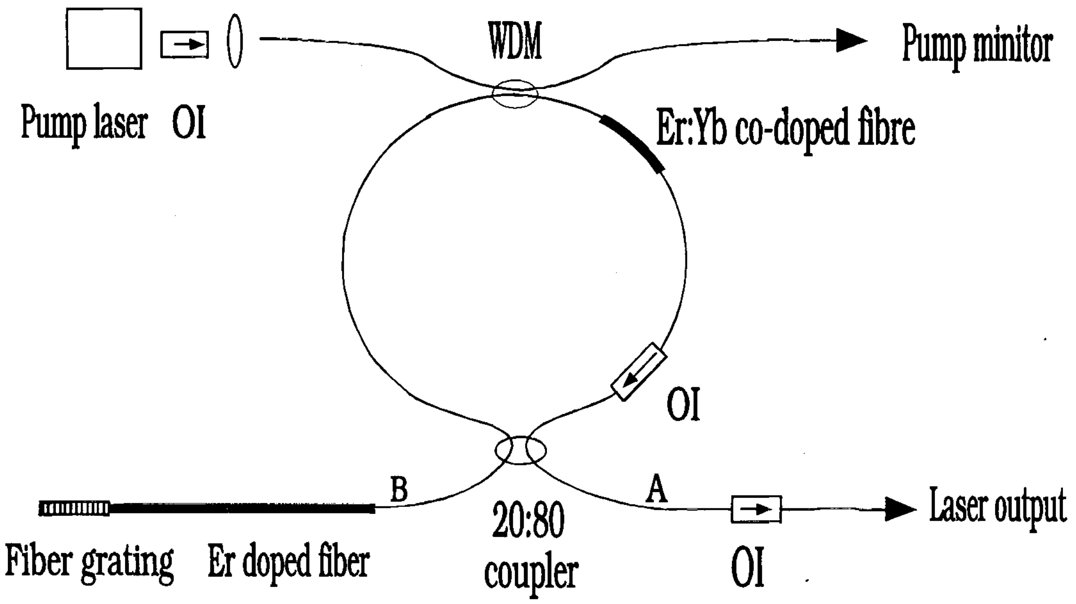
WDM
Pump minitor
Pump laser
OI
Er:Yb co-doped fibre
OI
B
A
Laser output
Fiber grating
Er doped fiber
20:80
coupler
OI

Fig. 1

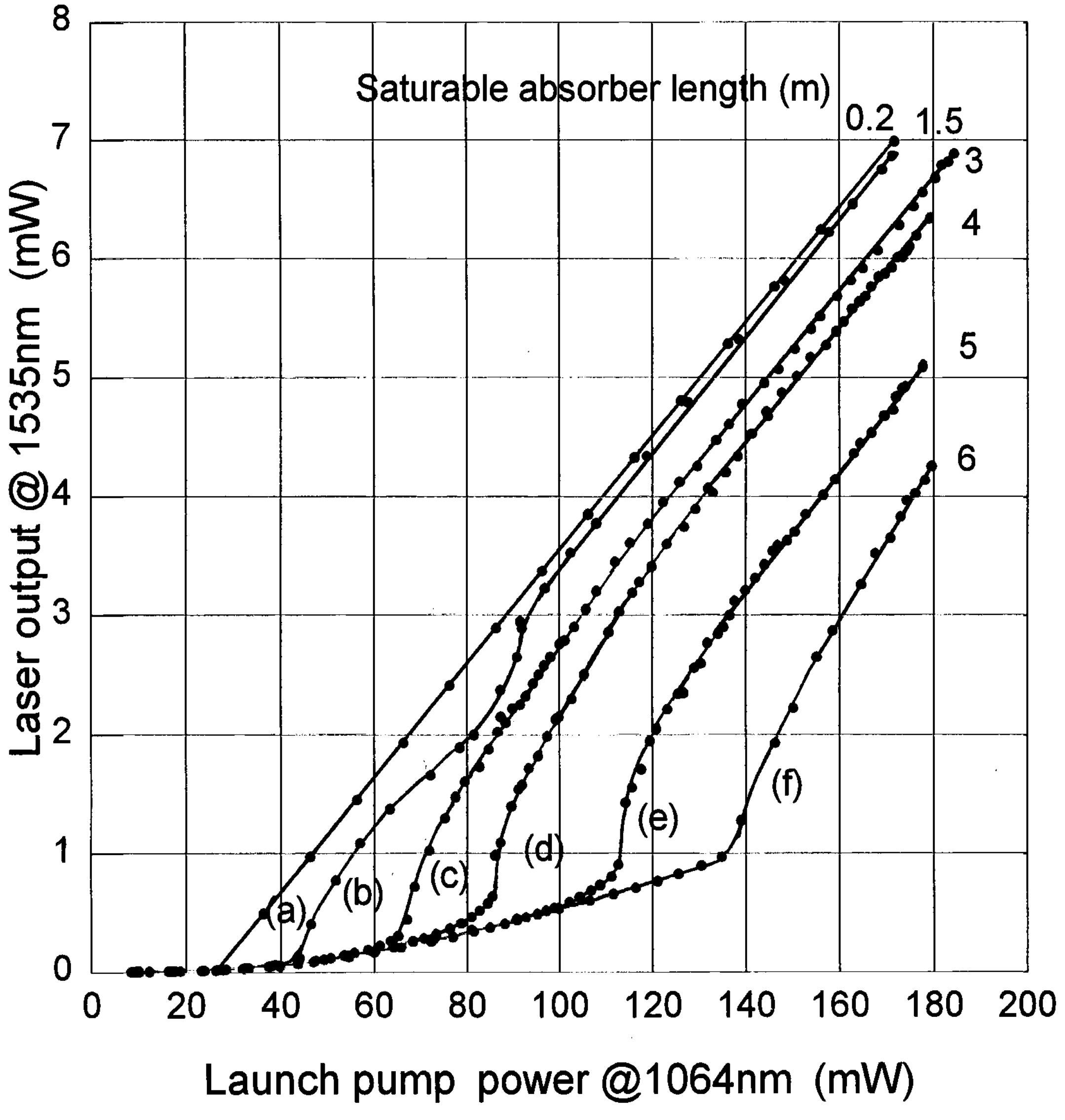
Saturable absorber length (m)
0.2
1.5
3
4
5
6
(a)
(b)
(c)
(d)
(e)
(f)
Laser output @ 1535nm (mW)
0
1
2
3
4
5
6
7
8
0
20
40
60
80
100
120
140
160
180
200
Launch pump power @1064nm (mW)

Fig. 2

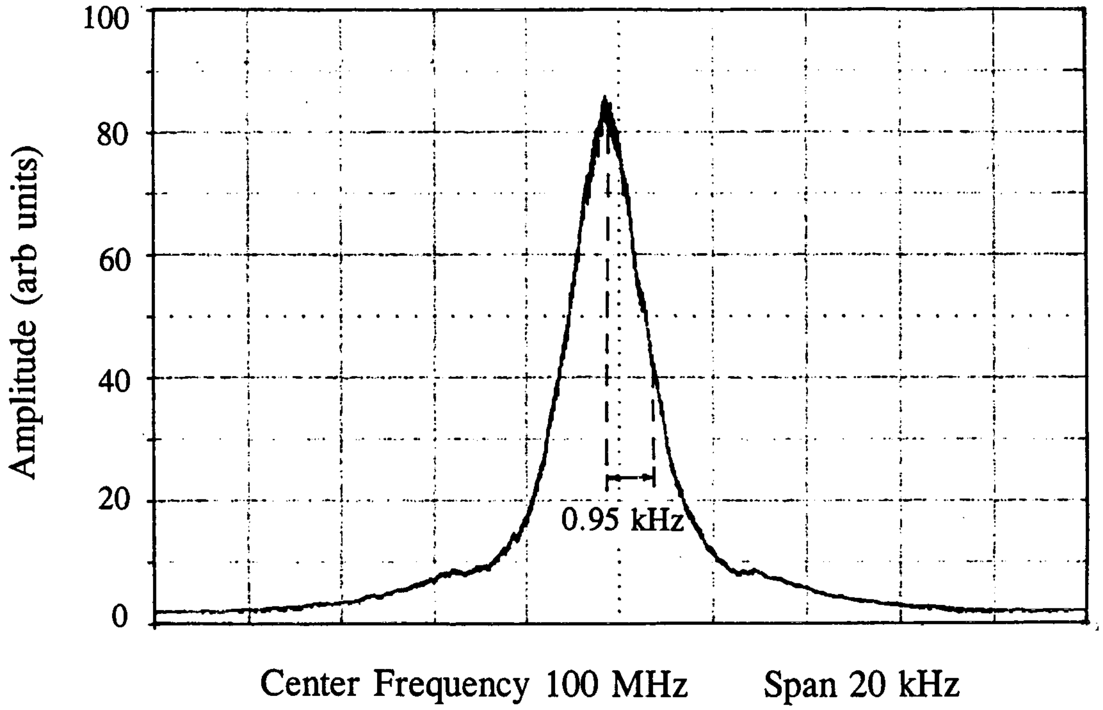
100
80
60
40
20
0
Amplitude (arb units)
0.95 kHz
Center Frequency 100 MHz
Span 20 kHz

Fig. 3

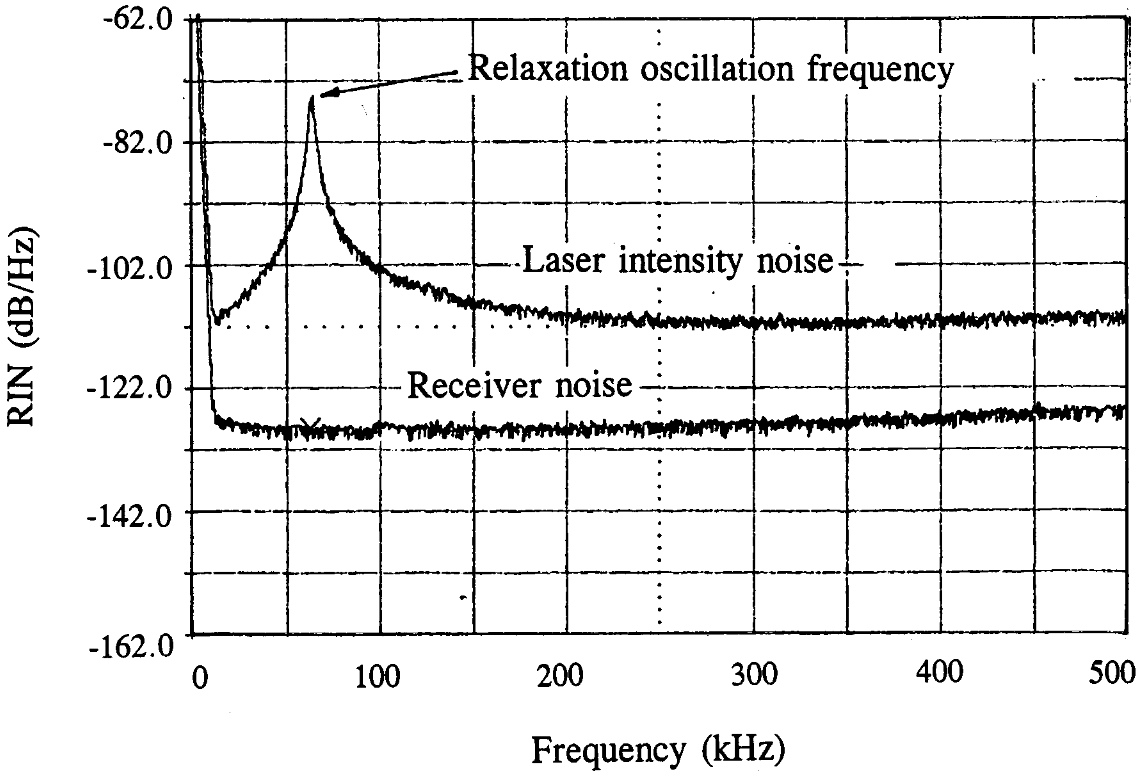
-62.0
-82.0
-102.0
-122.0
-142.0
-162.0
RIN (dB/Hz)
0
100
200
300
400
500
Frequency (kHz)
Relaxation oscillation frequency
Laser intensity noise
Receiver noise

Fig. 4