Noise characteristics of rare-earth-doped fiber sources and amplifiers

P.R.Morkel, R.I.Laming, G.J.Cowle & D.N.Payne

Optoelectronics Research Centre, University of Southampton,
Highfield, Southampton, S09 5NH, U.K.

1. ABSTRACT

The A.M. and F.M. noise mechanisms in a number of rare-earth doped fiber devices are reviewed. Spontaneous emission noise presents an ultimate limit to the performance of a number of fiber laser and amplifier devices and the paper concentrates primarily on this area. Important concepts are reviewed and experimental and theoretical data are presented.

2. INTRODUCTION

The noise characteristics of fiber laser and amplifier devices will determine the extent of their use in a number of applications. For example, the noise figure of an erbium-doped fiber amplifier (EDFA) sets an ultimate limit to receiver sensitivity when the amplifier is used as a pre-amplifier[1]. Also, the noise characteristics of broadband fiber laser and superfluorescent sources sets the limit for the SNR of a sensor such as a fiber-optic gyro using these sources[2]. In addition, the F.M. noise characteristics of fiber amplifiers[3] and single-frequency fiber sources[4,5] determines their use in coherent optical systems such as future coherent optical communication systems. In this paper we address the general issue of noise in rare-earth-doped fiber devices. Spontaneous emission noise sets a lower limit to the noise generated within optical amplifier devices and in many cases this limit is readily reached.

Noise in semiconductor devices has been widely studied (see e.g. refs. 6 & 7) and it has been found that carrier-density-induced refractive index variations also affects the noise characteristics and often is the limiting factor. Fiber devices do not show such an effect and can be seen to be advantageous in this respect.

3. DOPED-FIBER AMPLIFIERS

The mechanisms of noise generation with a rare-earth-doped fiber amplifier are:

3.1 Pump Noise feedthrough

Pump noise feedthrough results from temporal variations in the excited-state population due to variations in pump power. As the gain of the fiber device is proportional to the excited-state population, variations in excited-state population give rise to variations in signal output power and hence the signal can follow variations in the pump power[8]. However, pump noise feedthrough is not generally considered problematic for practical systems by virtue of the slow dynamics of the erbium-doped glass system[9]. This results from the large energy storage capability of the EDFA and means that pump-power fluctuations are only translated at low frequencies (<10kHz). Modern communication systems operate at frequencies >100MHz where excited-state fluctuations are heavily attenuated. In addition, practical pump sources for EDFA's are likely to include laser-diodes at 1485nm or 980nm which can be fabricated to give very-low-noise output.

The temporal variation in excited-state population in an EDFA, due to varying pump or signal fields can be described in terms of characteristic lifetimes. When the pump-band lifetime can be assumed to be negligible, the characteristic lifetime T_1 is given by[9]:

$$T_1 = \frac{1}{1/\tau_{21} + W_p + 2W_s} \qquad (1)$$

where τ_{21} is the metastable-level lifetime, W_p is the pump rate and W_s is the stimulated emission rate.

Under practical experimental conditions T_1 is in the range 100μs-1ms[9] which indicates that pump noise feedthrough as well as signal saturation will be attenuated at frequencies above 1-10kHz. For a 4-level system such as neodymium a similar expression to eq. 2 can be used if $2W_s$ is replaced by W_s is the denominator.

3.2 Spontaneous emission

As well as the shot noise associated with the amplified signal and the amplified spontaneous emission (ASE), the mixing on a detector of ASE with the amplified signal field gives rise to two additional noise products at the amplifier output, namely spontaneous-spontaneous and signal-spontaneous beat noise. This degrades the detected signal-to-noise ratio.

If we define the spectral width of the ASE at the amplifier output by:

$$\Delta\nu = \int_{\nu=0}^{\infty} \frac{P(\nu)d\nu}{P(\nu_0)} \qquad \Delta\nu' = \int_{\nu=0}^{\infty} \frac{P^2(\nu)d\nu}{P^2(\nu_0)} \qquad (2)$$

Where $P(\nu)$ represents the power-spectral-density of the ASE field and $P(\nu_0)$ represents the peak power-spectral-density. Then, for a detector bandwidth $B \ll \Delta\nu'$ the SNR at the output of an amplifier device, can be shown to be[10]:

$$SNR_{out} = \frac{(\eta GP)^2 B}{2e\eta[GP + 2n_{sp}h\nu(G-1)\Delta\nu] + 4\eta^2[n_{sp}GPh\nu(G-1) + (n_{sp}(G-1)h\nu)^2\Delta\nu']} \qquad (3)$$

where P is the signal input to the amplifier, G is the single-pass gain, η is the detector responsivity and n_{sp} is the population inversion parameter. The first two terms in the denominator represent signal and ASE shot noise and the third and fourth terms represent signal-spontaneous beat noise and spontaneous-spontaneous beat noise respectively.

The noise figure of an amplifier device is given by: $NF=10\log_{10}(SNR_{in}/SNR_{out})$. comparing then eq. 3 with the input SNR enables the noise figure to be derived. A shot noise limited input SNR is given by:

$$SNR_{in} = \frac{PB}{2h\nu} \tag{4}$$

With optical filtering, or with signal output powers substantially greater than the output ASE power, signal-spontaneous beat noise becomes the limiting noise mechanism and in this case we obtain:

$$NF = 10.\log\left(2n_{sp}\frac{(G-1)}{G}\right) \tag{5}$$

which for a high gain amplifier has a minimum value of 3dB for $n_{sp}=1$.

3.3 Experimental results

Fig 1 shows the noise figure measured for a 980nm pumped amplifier with pump power in the range 6-12mW and with signal input powers in the range -47 to -8 dBm[10]. The amplifier noise figure is seen to be determined by spontaneous-spontaneous beat noise in the input signal range -47dBm to -35dBm. Between -35dBm and -15dBm a noise figure of 2.9±0.4dB was measured, commensurate with dominant signal-spontaneous beat noise and a population inversion parameter n_{sp} at the minimum possible value of 1. Above -15dBm the noise figure is still signal-spontaneous limited, although saturation of the gain medium at these signal powers increases n_{sp} which degrades the noise figure.

Measurements of fiber-amplifier noise figure when pumping in-band at 1.49μm have also been performed[11]. In this case the proximity of pump and signal wavelengths precludes complete inversion of the erbium ions and hence a larger value of n_{sp} than 1 will result. A measured value of 5dB was obtained for signal wavelengths in the range 1520-1540nm. Calculations performed for a Ge/P/Si fibre to determine the minimum expected noise figure for an amplifier pumped in-band indicate that a noise figure around 5dB is the minimum expected[12].

3.4 Phase noise

In addition to amplitude noise, F.M. or phase noise is added to a coherent signal by an optical amplifier. The addition of randomly-phased spontaneous emission photons to a coherent signal field pulls the phase of the signal in a random manner and contributes to broadening of the spectrum of the signal. Such an effect is of importance in coherent optical communication systems where substantial spectral-broadening will be undesirable.

3.5 Experimental results

Fig. 2 shows an experimental configuration used to determine the degree of spectral broadening of a narrow-line signal after amplification in an EDFA[3]. An EDFA was incorporated within one arm of a balanced Mach-Zender interferometer into which light from a DFB semiconductor laser source with a 10MHz linewidth was coupled. Monitoring the output of the interferometer gave the degree of spectral broadening imparted by the amplifier. The common-mode configuration enabled spectral-broadening on a scale substantially less than the inherent linewidth of the laser source to be measured. A typical value for spectral-broadening of 15kHz measured at 17dB gain was observed, as shown in fig. 3. Such spectral-broadening will be additive for successive amplifiers. The measured values indicate that fiber amplifier phase noise is unlikely to limit the performance of high-bit-rate coherent communication systems.

4. SUPERFLUORESCENT SOURCES

4.1 Pump noise feedthrough

In common with the amplifier configuration, superfluorescent fibre sources are subject to pump noise feedthrough at low frequencies. The roll-off frequency above which pump-noise feedthrough reduces is determined by the pump and emission rates, along with the metastable-level lifetime. Although neodymium-doped fibres show pump-noise feedthrough at higher frequency than that of erbium-doped fibres (as the lifetime is shorter), at frequencies above ≈10kHz, pump noise feedthrough is unlikely to be problematic. As with the amplifier configuration, low-noise laser-diode pump sources can be used to further minimise this effect.

4.2 Excess photon noise

Broadband thermal-type sources such as superfluorescent fibres show excess photon noise due to beating of different parts of the optical spectrum together. This noise source has been described by Hodara[13] and is the same as spontaneous-spontaneous beat noise in an optical amplifier. The temporal photocurrent fluctuations, $<\Delta I_s^2>$, produced in a detector illuminated with light from a broadband fibre source can be written[2]:

$$\langle \Delta I_s^2 \rangle = 2e\langle I_s \rangle B + \frac{2}{m}\frac{\langle I_s \rangle^2}{\Delta\nu'}B \qquad (6)$$

where $<I_s>$ is the mean detected photocurrent, B is the receiver bandwidth, m is the number of transverse modes in the output and $\Delta\nu'$ is defined in eq. 2.

The first term in eq. 4 represents the usual shot noise and the second term represents excess photon noise. Note that the excess photon noise power is inversely proportional to the optical linewidth $\Delta\nu'$.

4.3 Experimental results

Fig. 4 shows experimental results for the noise in the output of an erbium-doped fiber superfluorescent source. The source output had a spectral width of 2nm FWHM. Also included in fig. 4 is the characteristic of a narrow-line He-Ne laser for comparison. The He-Ne laser is seen to be shot-noise-limited, while the superfluorescent source characteristic is seen to be determined by excess photon noise within the same range of signal output powers.

5. FIBER LASERS

Fiber laser structures show noise due to a number of factors. Amplitude fluctuations due to relaxation oscillations and excess photon noise in multi-mode devices are observed. In addition, spontaneous emission determines the minimum linewidth of fiber laser spectra, in common with other laser devices.

5.1 Relaxation oscillations

By virtue of feedback the optical field intensity in a resonant fibre laser structure has a resonant oscillation frequency determined by the cavity lifetime, the active ion lifetime and the rate of pumping above the laser threshold level. The relaxation oscillation frequency, $\omega_{ro,}$ for a 4-level system is[14]:

$$\omega_{ro} = \sqrt{\frac{P_s}{P_{sat}\tau_f\tau_c}} \tag{7}$$

Where P_s is the intra-cavity power, P_{sat} is the saturation power and τ_f & τ_c are the fluorescent and cavity lifetimes respectively.

The decay time constant of the oscillations is[14]:

$$\tau_{ro} = 2\tau_f\left(\frac{P_{sat}}{P_s}\right) \tag{8}$$

For a laser operating at 2x threshold, P_s=P_{sat} and the decay time constant of the oscillations is $2\tau_f$ which for Nd-doped fibres is ≈1ms. In common with other laser devices and driven oscillators in general, fibre lasers are subject to ringing or relaxation oscillations when the system is perturbed at the resonant frequency. Such perturbations can be mechanical, such as acoustic, or optical, such as pump power or external feedback variations. In a typical system where a fibre laser structure may be subject to broadband perturbations, the component of the perturbation at the relaxation oscillation frequency can give rise to substantial amplitude fluctuations. This is particularly so for long fibre laser structures which, by virtue of the long cavity lifetime, have relaxation oscillation frequencies <10kHz, where acoustic perturbations may be substantial. In general, fiber laser structures fabricated from metres of fibre are typified by relaxation oscillation frequencies lower than those of other laser devices, such as semiconductor lasers. Below ~1MHz the amplitude fluctuations in the output of a fibre laser are likely to be dominated by relaxation oscillations.

5.2 Spontaneous emission

5.2.1 Relative intensity noise in narrow-line lasers

The limiting noise mechanism in the output of a narrow-line fibre laser is likely to be the signal shot noise, or alternatively, beating of the signal with the residual amplified spontaneous emission. The latter mechanism is equivalent to signal-spontaneous beat noise in the fibre amplifier, although in the laser case the ASE power becomes clamped at laser threshold and does not increase with pump power above threshold.

Hence the relative intensity noise (RIN) due to spontaneous emission decreases as the laser is operated higher above threshold. The RIN due to these two mechanisms can be written:

$$RIN = \frac{2}{P_s}\left(e/\eta + \frac{2P_{ase}^{(th)}}{\Delta\nu} \right) \tag{9}$$

where P_s is the laser output power, $P_{ase}^{(th)}$ is the threshold ASE power, η is the detector responsivity, e is the electron charge and $\Delta\nu$ is the spectral width of the ASE. The first term in parenthesis represents shot noise and the second term noise due to beating of the signal with residual ASE. As can be seen from eq. 9, the RIN decreases as the laser is operated higher above threshold. Also, to achieve the lowest possible RIN, a low-threshold cavity is advantageous in order to reduce $P_{ase}^{(th)}$.

5.2.2 Limiting linewidth of narrow line lasers

It is well known that the coupling of randomly-phased spontaneous emission photons into a single-mode laser field sets the ultimate limit to the linewidth of the emission. The limiting linewidth was first derived for a laser device by Schawlow & Townes and is generally termed the Schawlow-Townes limit. The phase noise process which gives rise to it can be seen to be the same mechanism as gives rise to spectral broadening in the fiber amplifier described before. The Schawlow-Townes laser-linewidth limit ($\Delta\nu_s$) can be written[15]:

$$\Delta\nu_s = \frac{4\pi h\nu}{P_s}(\Delta\nu_c)^2 \tag{10}$$

where $h\nu$ is the photon energy, P_s is the laser power and $\Delta\nu_c$ is the passive cavity linewidth. Reduction of the passive cavity linewidth $\Delta\nu_c$ reduces the laser linewidth and hence fibre cavities which can be metres in length have the potential for very narrow linewidth emission. Note also that the linewidth, or phase noise, reduces with increasing laser power in a similar manner to the RIN described before.

5.3 RIN in broadband fiber lasers

Broadband fiber lasers which operate simultaneously on a number of longitudinal modes are subject to excess photon noise in the same manner as broadband superfluorescent sources. For the laser, however, the noise spectrum is different in that the optical spectrum consists of a set of discreet lines separated by the laser cavity mode-spacing. This gives rise to an RF spectrum of the output which consists of a comb of lines due to intermodal beating, which should be contrasted with the superfluorescent source, where the noise spectrum is flat over regions of electronic interest. It has been shown[13] that for a laser operating on a number of longitudinal modes (>5 modes), the noise power is the same as for a thermal-type source. Over a restricted electronic frequency range, however, the number of intermodal beats within the range of interest will determine the noise characteristics. If the range of interest is less than the intermodal beat frequency, then the device is likely to show the same noise characteristics as a narrow-line source which is determined by ASE. Therefore, it can be said that the noise characteristics follow eq. 9 if the receiver bandwidth is less than the inter-modal beat frequency. For receiver bandwidths substantially greater than the inter-modal beat frequency, the noise characteristic will follow eq. 6, ie:

$$B<\delta\nu \qquad RIN = \frac{2}{P_s}\left(e/\eta + \frac{2P_{ase}^{(th)}}{\Delta\nu_{ase}}\right) \tag{11}$$

$$B>\delta\nu \qquad RIN = \frac{2e}{P_s\eta} + \frac{2}{m\Delta\nu'}$$

where $\delta\nu$ is the inter-modal beat frequency.

6. CONCLUSIONS

In this paper noise mechanisms in a number of active fibre devices have been reviewed. These include the doped-fibre amplifier, fiber superfluorescent sources and fibre laser devices. A.M. and F.M. noise mechanisms have been identified. It is seen that all devices are subject to pump noise at low frequencies. In addition, mixing of the ASE field with itself and with signal fields give rise to temporal fluctuations in the output of each of the devices. The resonant fibre laser configuration is also seen to be highly sensitive to perturbations at its ringing or relaxation oscillation frequency. Phase noise caused by addition of randomly-phased spontaneous emission photons to a coherent signal field in single-mode fibre lasers and the amplifier has also been quantified.

7. REFERENCES

1. R.Olshansky, "Noise figure for erbium-doped optical fibre amplifiers", El. Lett., vol. 24, no. 22, Oct. 1988.

2. P.R.Morkel, R.I.Laming & D.N.Payne, "Noise characteristics of high-power doped-fibre superluminescent sources", El. Lett., Vol. 26, no. 2, Jan. 1990.

3. G.J.Cowle, P.R.Morkel, R.I.Laming & D.N.Payne, "Spectral broadening due to fibre amplifier phase noise", El. Lett., Vol. 26, no. 7, March 1990.

4. I.M.Jauncey, L.Reekie, J.E.Townsend, D.N.Payne & C.J. Rowe, "Single longitudinal-mode operation of a Nd^{3+}-doped fibre laser", El. Lett., Vol 24, no. 1, Jan 1988.

5. P.R.Morkel, G.J.Cowle & D.N.Payne, "Travelling-wave erbium fibre ring laser with 60kHz linewidth", El. Lett., Vol. 26, no. 10, May 1990.

6. T.Mukai, Y.Yamamoto & T.Kimura, "S/N and error rate performance in AlGaAs semiconductor laser preamplifier and linear repeater systems", IEEE J. Quantum Electron., Vol. QE-18, no. 10, p.1560, 1982.

7. C.H.Henry, "Theory of the linewidth of semiconductor lasers", IEEE J. Quantum Electron., Vol. QE-18, no. 2, pp.259-267, 1982.

8. R.I.Laming, L.Reekie, P.R.Morkel & D.N.Payne, "Multi-channel crosstalk and pump-noise characterisation of erbium-doped fibre amplifiers", El. Lett., vol. 25, no. 7, pp. 455-456, March 1989.

9. E.Desurvire, C.R.Giles & J.R.Simpson, "Gain dynamics of erbium-doped fiber amplifiers", SPIE vol. 1171, Fiber Laser Sources and Amplifiers (1989), pp. 103-117.

10. R.I.Laming & D.N.Payne, "Noise characteristics of erbium-doped fiber amplifier pumped at 980nm", IEEE Photonics Technology Letters, Vol. 2, no. 6, pp.418-421, June 1990.

11. C.R.Giles, E.Desurvire, J.L.Zyskind & J.R.Simpson, "Noise Performance of Erbium-Doped Fiber Amplifier Pumped at 1.49μm, and Application to Signal Pre-amplification at 1.8 Gbits/s", IEEE Photonics Technology Letters, Vol. 1, no. 11, pp.367-369, Nov. 1989.

12. W.J.Miniscalco, L.J.Andrews, B.A.Thompson, T.Wei & B.T.Hall, "The effect of glass composition on the performance of Er^{3+} fiber amplifiers", SPIE vol. 1171, Fiber Laser Sources and Amplifiers (1989), pp. 93-102.

13. H.Hodara, "Statistics of thermal and laser radiation", Proc. IEEE, Vol. 53, pp.696-704, 1965.

14. W.Koechner, Solid State Laser Engineering 2nd ed., Springer Verlag.

15. A.L.Schawlow & C.H.Townes, "Infrared and Optical Masers", Phys. Rev., Vol. 112, no. 6, pp.1940-1949, Dec. 1958.

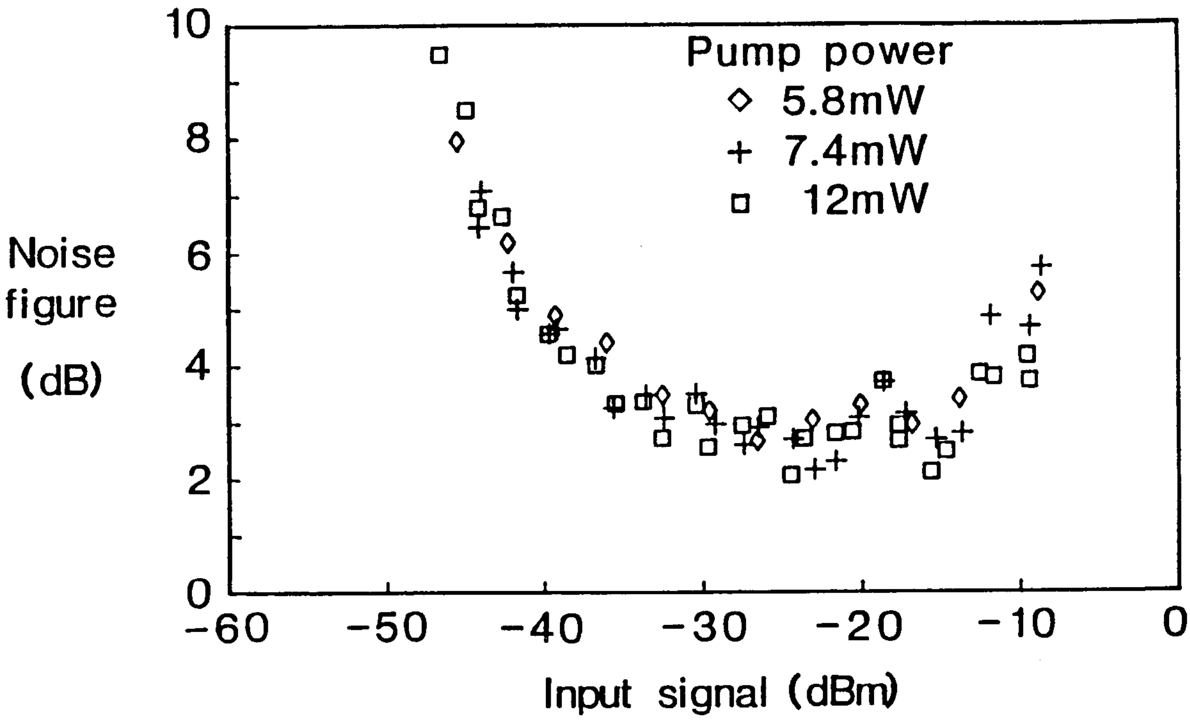

Fig. 1 Measured noise figure of a 980nm pumped EDFA. The amplifier had small signal gain of 21dB, 25dB & 26dB for the three pump powers indicated.

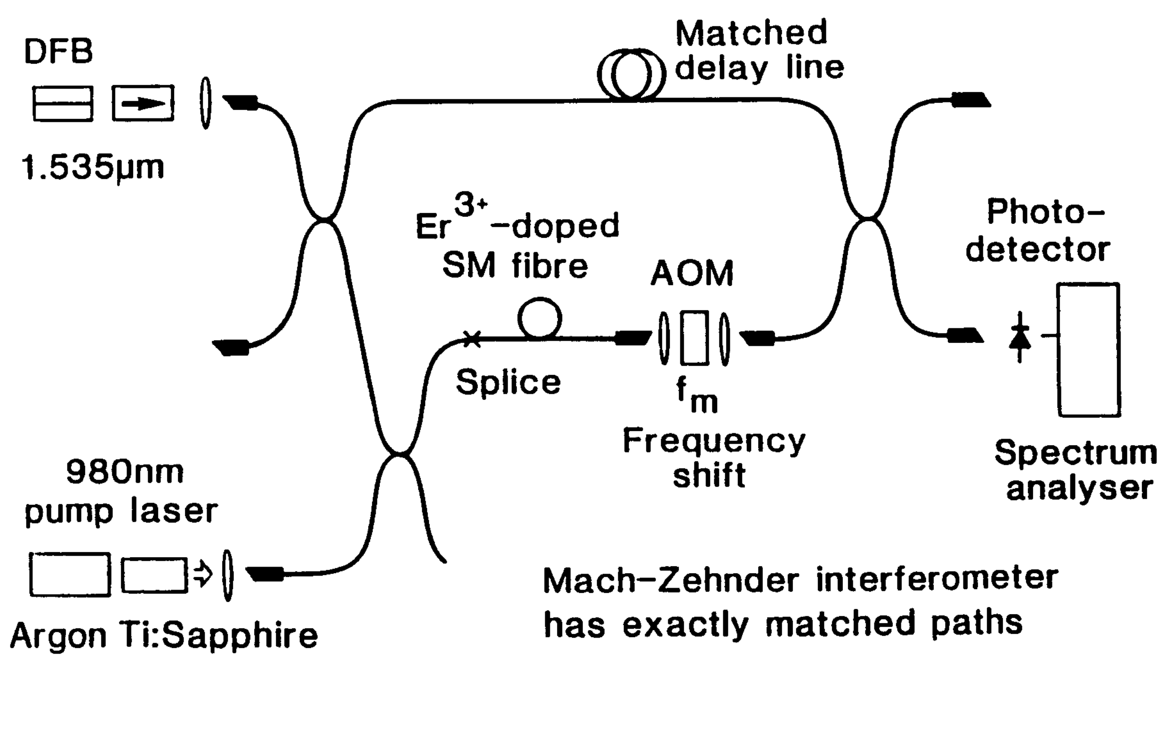

Fig. 2 Experimental configuration for determination of EDFA spectral broadening due to amplifier phase noise.

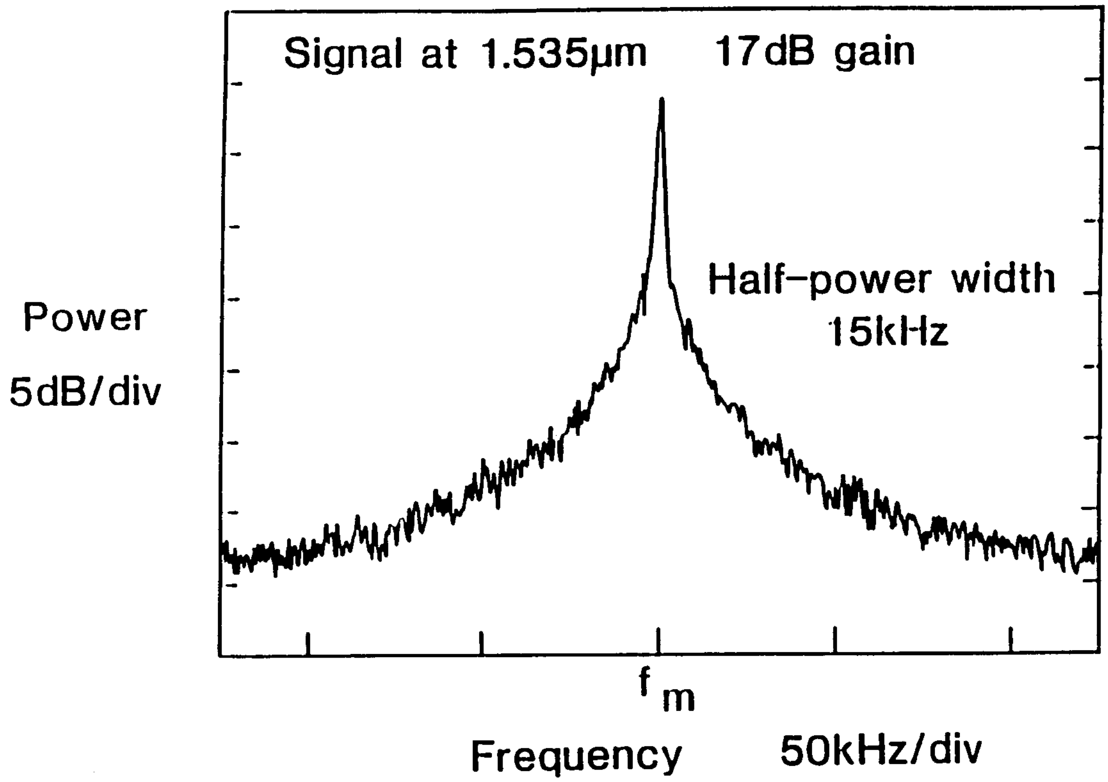

Fig. 3 EDFA spectral broadening measurement, interferometer output RF spectrum. This indicates spectral broadening of ≈15kHz on the 10MHz DFB laser signal.

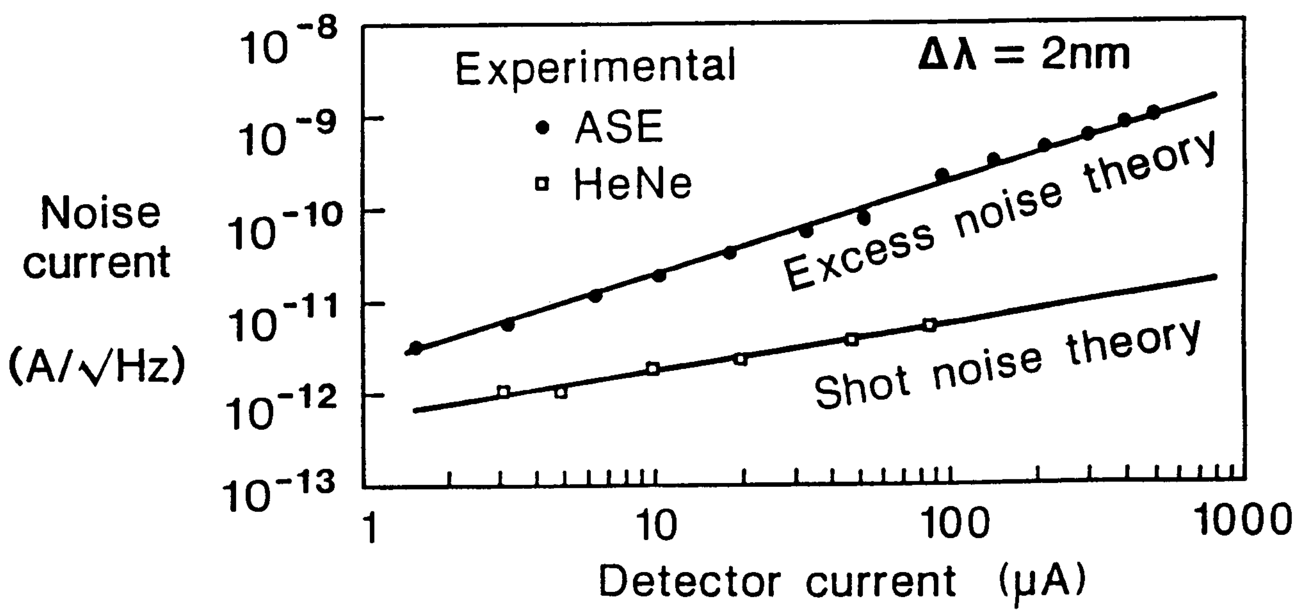

Fig. 4 Erbium-doped fiber superfluorescent source experimental and theoretical noise characteristic. The shot-noise-limited characteristic of a He-Ne laser output is included for comparison.