1566

An extended range OTDR system at 1.65μm based on delayed Raman amplification

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Abstract: This paper describes both theoretical and experimental results obtained in an investigation of a new technique for increasing the dynamic range of 1.65μm OTDR systems. The technique utilises delayed Raman amplification of 1.65μm signal pulse by a 1.53μm pump pulse. Amplification occurs when the two pulses overlap and this position is determined by the initial delay between the pulses and the fibre dispersion. An increase in dynamic range of 17.5dB has been observed and the OTDR backscattered Rayleigh signal was detected up to 100km. No significant noise penalty is introduced due to the directionality of the Raman gain.

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The use of Optical Time Domain Reflectometry (OTDR) is a well established technique for fibre fault location and loss distribution measurements along a length of fibre. In an OTDR system, a short pulse of light is transmitted down the sensing fibre and the Rayleigh backscattered signal is detected. The intensity of the backscattered light provides a measure of the loss in the fibre and the time between launching the light pulse into the fibre and obtaining the backscattered light provides a continuous measure of distance in the fibre. Being more sensitive to fibre macro-bending and micro-bending losses, an OTDR system operating at 1.65μm provides a more reliable technique of early system fault detection than systems operating at wavelengths of 1.3μm/1.55μm. The initial limitation of a 1.65μm OTDR system rested in the limited power available from 1.65μm laser diodes. The use of Raman amplification to amplify a 1.66μm laser diode pulse by 24.8dB before launching it down the end of a sensing fibre has recently been reported [1]. However, the maximum signal power that can be launched down the sensing fibre is limited by the onset of nonlinear effects at the front end of the sensing fibre.

In this letter, we report a novel technique of increasing the dynamic range of a 1.65μm OTDR system through the use of delayed Raman amplification within the sensing fibre. This method operates with the Raman pump pulse and the OTDR pulse both maintained just below their respective stimulated Raman thresholds at the front end of the fibre. The gain experienced by the OTDR pulse is achieved during the overlapping process of the two pulses. The Stokes pulse may double its energy, for example, if both the pump and OTDR pulses have the same width. The delayed amplification of the OTDR pulse allows greater pulse energy to be achieved at some distance from the front end of the sensing fibre, thereby increasing the dynamic range. The limiting threshold value is therefore no longer constrained to the front end of the sensing fibre.

The amplification achieved depends on the amount of energy available to amplify the OTDR pulse, which is determined by the peak intensity of the pump pulse which is limited by the stimulated Raman threshold, and the pump pulse width. Although the OTDR pulse width is limited by the system spatial resolution requirements, the pump pulse width may be considerably larger. This enables a larger amount of energy to be transferred to the signal pulse. The present study investigates a theoretical analysis of the Raman amplification process during the pump and OTDR pulse overlap, and is then compared to experimentally obtained results.

Our model analyses the Raman amplification of a 1.65μm pulse, representing the signal pulse in an OTDR system, by a 1.53μm pump pulse. The two pulses are launched in the single mode sensing fibre with a time delay, Δt, between the pump and signal pulse. The distance from the front end of the sensing fibre to where the two pulses overlap is given by the fibre dispersion parameter D and Δt.

For the analysis, the intensity profiles of the pump and signal pulses were measured experimentally and sampled at 200 equally spaced segments. These values were then used in the computer model. The overlapping gain process was modelled by incrementing one pulse with respect to the other by one segment at a time and calculating the depletion of the pump pulse and Raman amplification of the signal pulse with the following pair of coupled equations:

$$dP_s / dz = (g_R / A_s)\, P_s P_p - \alpha_s P_s \qquad (1)$$

$$dP_p / dz = -(g_R / A_p)(\omega_p / \omega_s) P_s P_p - \alpha_p P_p \qquad (2)$$

where the subscripts p and s refer to the pump and Stokes shifted 1.65μm probe pulses respectively; α is the absorption constant of the fibre; A is the effective cross-section area, and g_R is the nonlinear Raman gain constant at 1.53μm. The backscattered Rayleigh signal generated by the 1.65μm pulse was then computed with a spatial resolution of 100 metres. Assuming that the Raman gain constant has a value of 9.2×10^{-14} m/W at a wavelength of 1.064μm [2,3], the Raman gain constant which is inversely proportional to the pump wavelength at a pump wavelength of 1.53μm is given by:

$$\begin{aligned} g_R &= (1.064/\lambda_p) \times (9.2\times10^{-14}) \qquad (3) \\ &= 6.4 \times 10^{-14} \text{ m/W.} \end{aligned}$$

The set-up for the experiment is as shown in Figure 1. A high power 1.53μm pulsed source recently developed was used to generate the Q-switched pulses [4]. The pulses were then passed through a 90/10 coupler. Pulses at the wavelength of 1.65μm were generated in the

90% arm through a process of stimulated Raman process along 300metres of standard telecommunications grade fibre. The generated 1.65μm pulses were then separated from the residual 1.53μm pump pulses with a narrow band pass filter centred at a wavelength of 1.65μm, producing pulses 1.0W of peak power, pulse width of 18ns, and a 3dB optical bandwidth of 25nm. Raman amplification occurs when the 1.53μm pulses from the 10% arm and 1.65μm pulses overlap due to dispersion within the sensing fibre. The delay between the two pulses before the overlap down the sensing fibre is determined by adjusting the length of fibre on the 10% arm of the coupler. The two arms are then recombined using a 66/34 wavelength division multiplexer (WDM), biased to obtain the maximum backscattered signal.

The operating wavelengths for the two pulses concerned are within the anomalous-dispersion regime for standard telecommunications fibre, so pulses at 1.53μm travel faster than pulses at 1.65μm. The 1.53μm pulses were therefore adjusted such that it was propagating behind the 1.65μm pulses at the front end of the fibre and would overlap at a distance along the sensing fibre. The 1.65μm pulses are then amplified by the process of Raman amplification as the 1.53μm pulse passes through it.

The experiment was carried out for a length of about 100km of sensing fibre, consisting of 6 drums of standard telecommunications fibre, where the radius of the drums were 14cm. The Rayleigh backscattered measurements are as shown in Figure 2. Experimental results demonstrate an increase in dynamic range of 17.5dB for the OTDR trace with the amplification process. The dotted line in Figure 2 denotes the calculated OTDR trace based on the governing differential equations and experimental pulse powers, where a comparison with the experimental results is made. The small difference between the two rates of Raman amplification in the calculated and experimental curve is due to the larger pump depletion from the tail of the experimental Stokes pulse and the step-like losses in the experimental results are due to splice losses. Various equivalent steps of peak pump power levels were also used for the experiment with the same peak signal pulse, and the result is shown in Figure 3. As can be seen, the corresponding peak amplification is reduced for smaller peak pump power levels. The smaller OTDR power levels in Figure 3 as compared to the OTDR trace in Figure 2 is due to a small bend loss in the fibre drum before the 90/10 coupler. Figure 4 shows the net gain achieved for the OTDR system against the relevant peak pump power levels ranging from 1 to 5W. There is a reduction in the rate of increase of net gain with increasing peak pump power levels. This is due to the saturation of the Raman amplification process, in which the Stokes pulse is generating higher order Stokes signals.

Through a process of delayed Raman amplification and the utilisation of a high power Q-switched Erbium fibre laser, a novel technique of increasing the dynamic range 1.65μm OTDR system has been developed. Experimental results which have been theoretically modelled have demonstrated an increase in dynamic range of 17.5dB within the sensing fibre. By means of fibre dispersion, the 1.53μm pulse passes through and amplifies the 1.65μm pulse at some distance along the fibre. The amplification is achieved without significant noise penalty as a result of the directionality of the Raman gain, and is ideally suited for backscattered measurements. The OTDR system operating at the pump and Stokes wavelengths of 1.53μm and 1.65μm respectively minimises the fibre attenuation during propagation and is therefore most appropriate for long lengths of sensing fibre.

The OTDR system reported here is based on the Rayleigh backscattered measurements. It may however also be employed for other applications of distributed measurements, such as distributed strain and temperature sensing based on Brillouin and Raman scattering. As the limiting threshold value of the amplified the signal pulse may be achieved at some distance down the sensing fibre, a new generation of extended range distributed sensors is feasible.

Acknowledgements: This work is supported by a UK Engineering and Physical Sciences Research Council (EPSRC) CASE award in collaboration with York Sensors Ltd, Romsey and the Overseas Reseach Students (ORS) Awards Scheme.

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Figure 1- Set-up for the Raman amplification experiment

Figure 2- (a)Theoretical and (b) Experimental results for the Raman amplification process

Figure 3- OTDR traces of varying pump power levels from 1 to 5W

Figure 4- Net gain achieved for the OTDR system for pump power levels from 1 to 5W

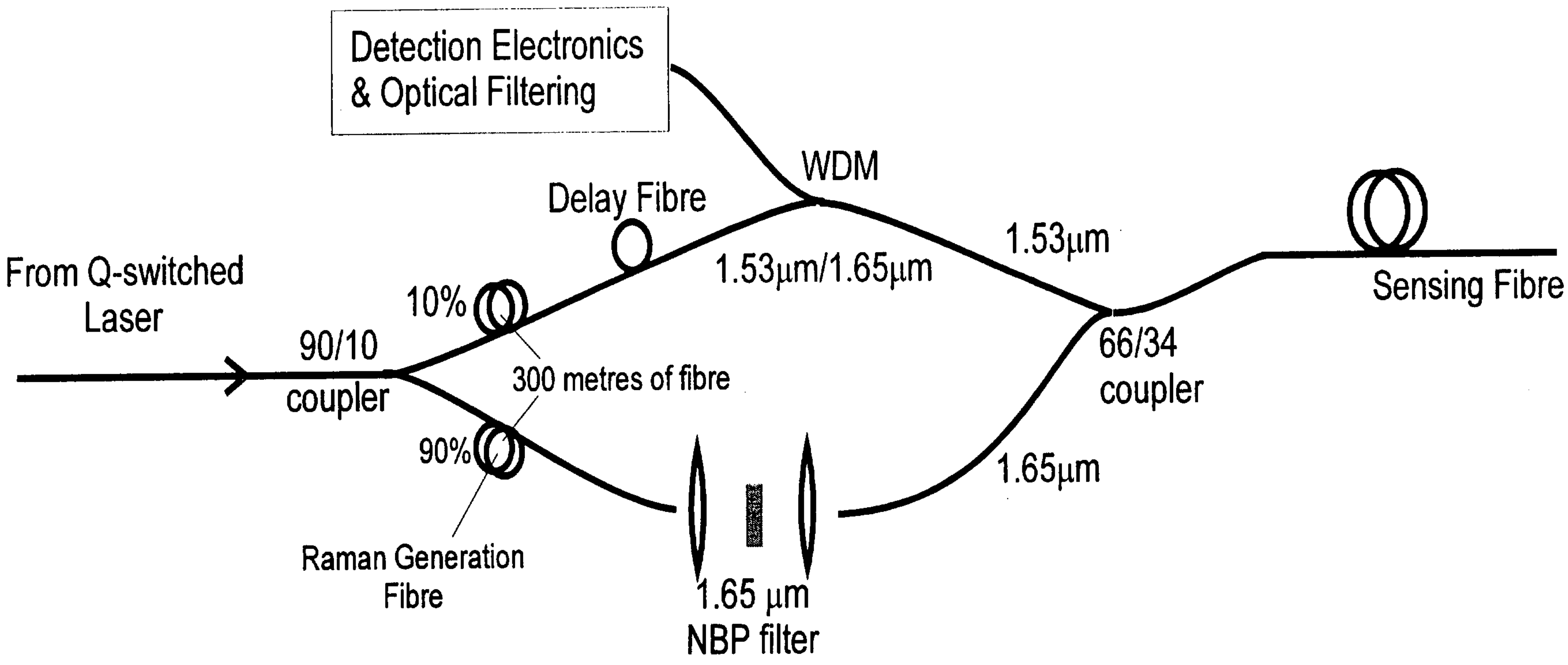
Detection Electronics
& Optical Filtering
WDM
Delay Fibre
1.53µm
From Q-switched
Laser
10%
1.53µm/1.65µm
Sensing Fibre
90/10
coupler
300 metres of fibre
66/34
coupler
90%
1.65µm
Raman Generation
Fibre
1.65 µm
NBP filter

FIGURE 1

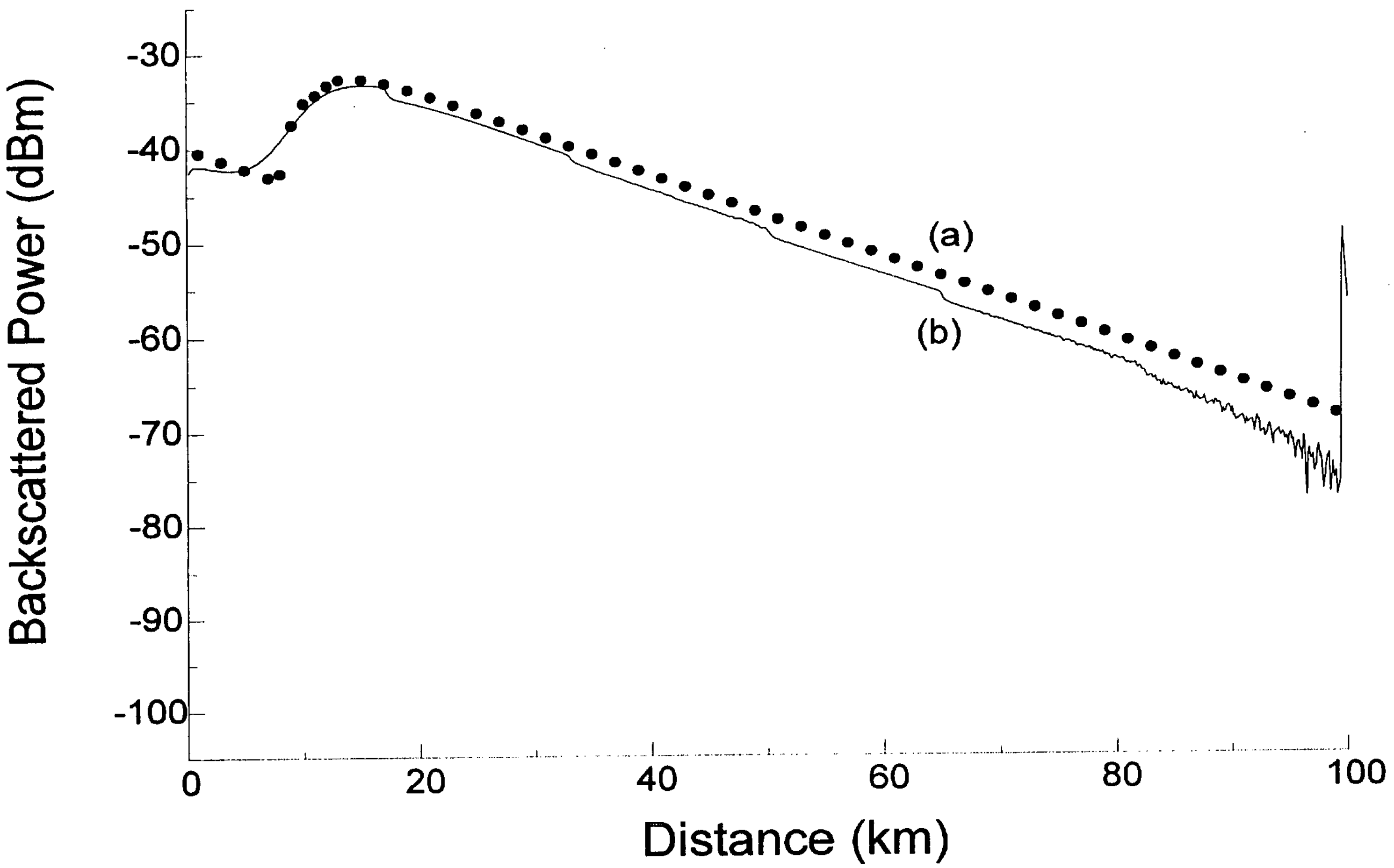
Backscattered Power (dBm)
-30
-40
-50
-60
-70
-80
-90
-100
0
20
40
60
80
100
Distance (km)
(a)
(b)

FIGURE 2

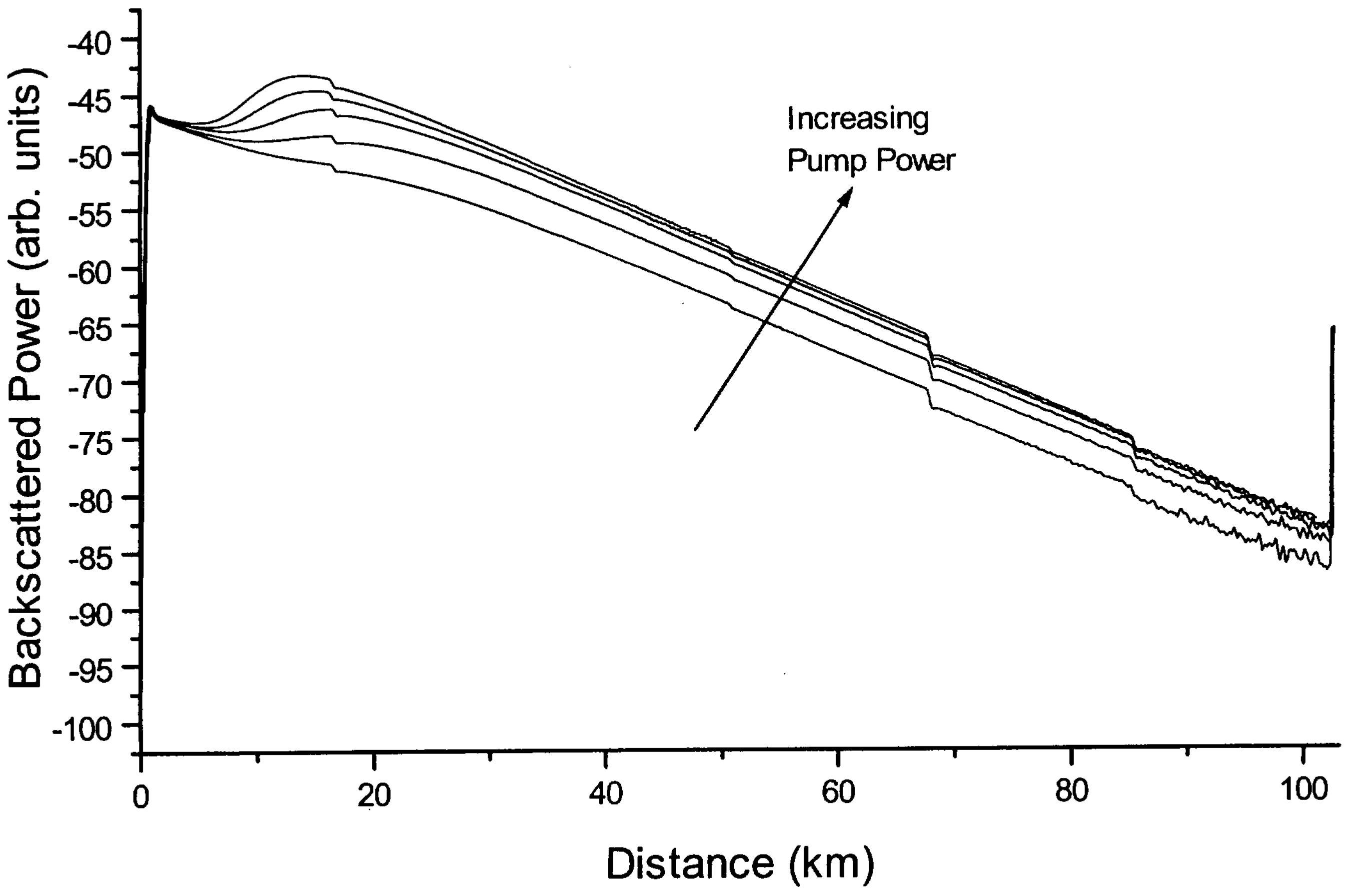
Increasing
Pump Power
Backscattered Power (arb. units)
-40
-45
-50
-55
-60
-65
-70
-75
-80
-85
-90
-95
-100
0
20
40
60
80
100
Distance (km)

FIGURE 3

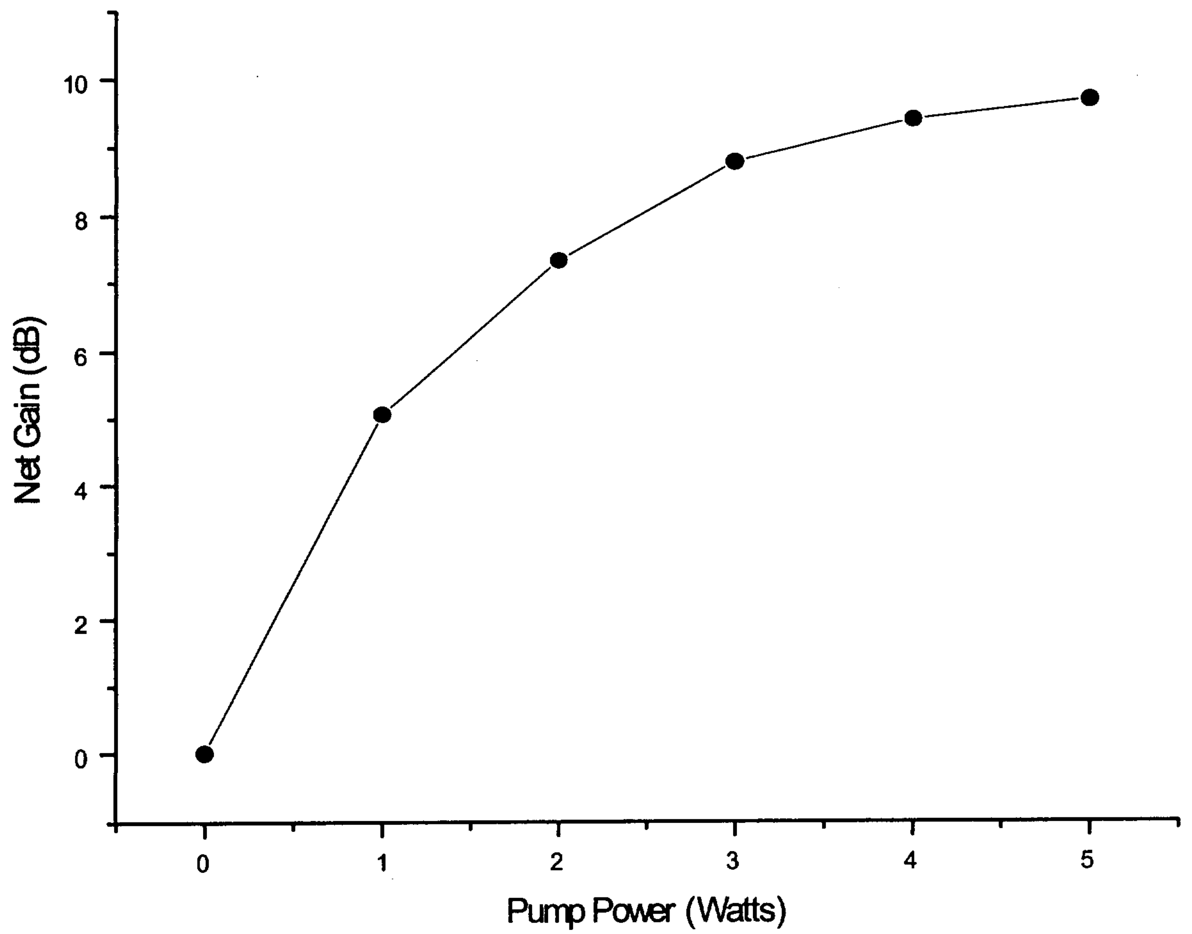

FIGURE 4