Linewidth and Phase Noise Characteristics of DFB Fibre Lasers

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ABSTRACT

The anomalous linewidth behavior in a DFB fiber laser is investigated. It is shown that not only does the linewidth deviate drastically from the Schawlow-Townes linewidth formula by increasing with pump and laser power, but it also varies significantly with the pumping configuration used. These results have potentially important implications for the design and operation of such fiber lasers.

Keywords: Distributed feedback lasers, optical fiber lasers, laser noise, laser stability.

1. BACKGROUND

Short cavity single frequency fiber lasers have been a topic of continued interest since the early work of Ball *et al* on Er-doped DBR (distributed Bragg reflector) fiber lasers[1]. Their size, simplicity, ease of fabrication, compatibility to transmission fiber and optical emission characteristics make them attractive for a number of applications, particularly in the sensing area. However, there have been few detailed experimental investigations on the linewidth or phase noise characteristics of these lasers, with much of the work focused on improving the efficiency and output power through fiber, cavity, or grating design[2-4]. With the widespread adoption of Er/Yb fibers, laser efficiencies in the tens of percent are now easily achievable[5]. An implicit assumption, however, in many of these designs is that the attainable laser frequency noise characteristics will not be substantively compromised by the proposed modifications. This is clearly an important assumption as it is usually the single frequency characteristics of these kinds of fiber lasers that make them so attractive. To our knowledge, however, there has been very little evidence shown to verify the extent to which this assumption is true.

To date, the phase noise properties of these fiber lasers continue to fail to measure up to that achievable in bulk solid state lasers. This is perhaps surprising, considering that predictions of the intrinsic linewidths of fiber lasers based on the well-known Schawlow-Townes formula indicate linewidths of just 60 Hz or less[6]. A common suggestion as to why the observed linewidths remain far above their theoretical limit is that the increased noise is caused by environmental perturbations, such as external vibration and acoustic noise, which the fiber laser may be more susceptible to. The inference then is that this issue is primarily a packaging problem, which could be solved by better mechanical designs in holding the fiber, vibration isolation, etc.

The purpose of this work is to present experimental data which strongly suggest that the anomalously large linewidths of these fiber lasers should be more accurately viewed as an intrinsic aspect of these lasers, and that designs for maximizing output power and efficiency likely need to take into account potential trade-offs in their single frequency characteristics.

2. EXPERIMENTAL DETAILS

The experimental configuration is shown in Fig. 1. The DFB (distributed feedback) fiber laser is constructed from a 125 μm diameter fiber, containing an Er/Yb-doped phosphosilicate core surrounded by a photosensitive boron ring, similar in structure to that reported before[7]. The small signal absorption at 980 nm is 1200 dB/m (virtually all of it saturable), and 45 dB/m at 1530 nm. The uv-written grating length L is 5 cm, with a $\lambda/4$ phase shift located slightly off-centre, about 3 mm from the mid-point of the grating. This asymmetry enables the output power to be emitted predominantly from one end of the laser, which is attractive from a practical point of view. The grating strength κ was estimated as κL~10. The fiber laser is mounted on a temperature-controlled copper heat sink, and pumped with a 980 nm laser diode. Care was also taken to minimize the amount of Er/Yb fiber extending beyond the laser grating cavity, by splicing undoped fiber as close to the ends of the fiber grating as was practicable (to within 1-2 mm). The laser linewidth is measured using a delayed self-heterodyne set-up, with a 60 km fiber delay line.

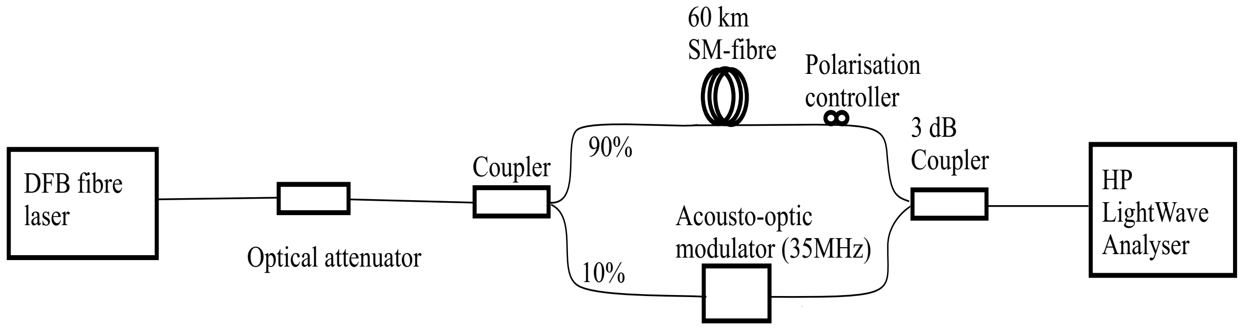
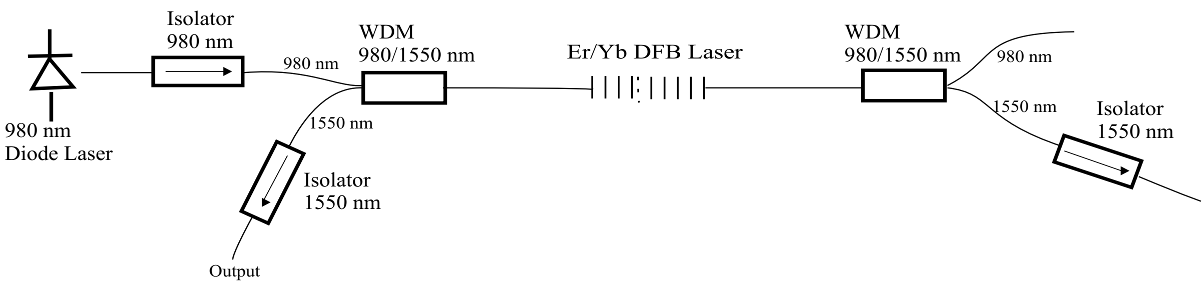
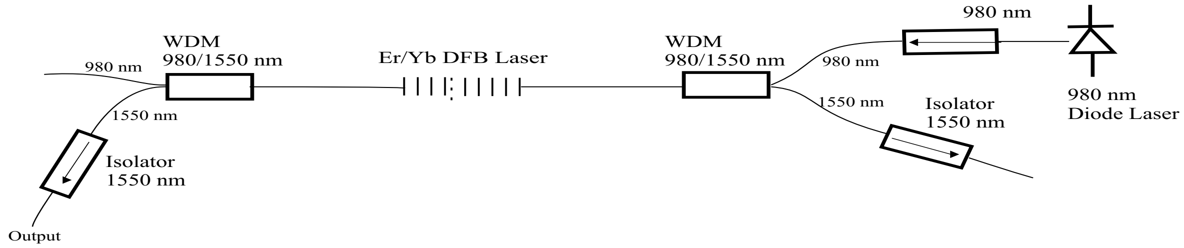


Fig. 1 Experimental configuration showing the linewidth measurement set-up

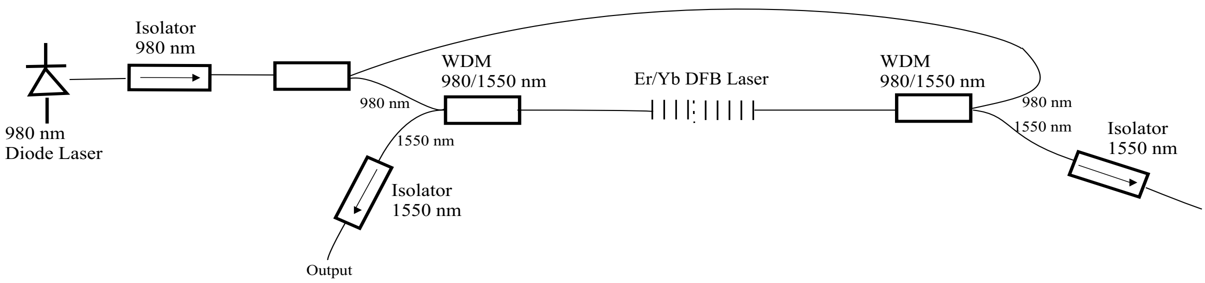
The fiber laser was investigated by pumping through 3 different configurations (Fig. 2). The first configuration, called backward pumping, consists of the pump power counterpropagating to the main laser output, i.e. the pump is coupled in at the end nearer to the grating phase shift. The second - forward pumping - has the pump coupled in from the opposite end of the grating, i.e. the far end with respect to the phase shift. In the third scheme - dual pumping - the pump is split equally in two and coupled into the fiber laser at both ends. A 980 nm optical isolator is used at the output of the pump laser in all cases to prevent undesired optical feedback from destabilising the pump diode. 1550 nm optical isolators were also placed at both output ends of the fiber laser to ensure that the linewidth behavior being studied is not compromised by unintended feedback effects into the DFB laser. The lasing threshold, output power, and linewidth were all measured for the 3 pumping configurations. The laser was confirmed to be operating in a single polarization state.



(a)



(b)



(c)

Fig. 2 Schematic of the laser pumping configurations used in the investigations: (a) backward pumping, (b) forward pumping, and (c) dual pumping configuration

3. RESULTS AND DISCUSSION

Fig. 3 shows the threshold and output power characteristics of the fiber laser under the 3 pumping configurations. It is easy to see that the backward pumping scheme gives the lowest threshold and highest efficiency, while the dual pumping scheme is the worst in these aspects. This behavior is easily modeled, and can be explained by the asymmetry of the grating design and the different pump absorption within the grating for the different pumping configurations. The pump intensity within the grating is strongest at the grating input, saturating the Yb absorption there first, and then decays during propagation as it is strongly absorbed. The resulting unabsorbed pump power is less than 1%. The lasing threshold approximately corresponds to the pump power where the laser light experiences gain on one side of the phase shift and loss on the other. Because of the asymmetry, this is achieved for lower pump powers in the backward pumping configuration than for forward pumping. For dual pumping, on the other hand, where each input port only receives half the pump power, the pump absorption is generally a little larger according to the later onset of the saturation of the Yb transition. This results in the highest lasing threshold for this configuration. Therefore, if maximizing efficiency and output power is the over-riding criterion, then backward pumping is clearly the configuration to adopt. We note that the laser output was highly asymmetric for all 3 pumping configurations, which is expected due to the location of the grating phase shift: ~95% of the total laser output was measured to come out the end nearer to the phase shift.

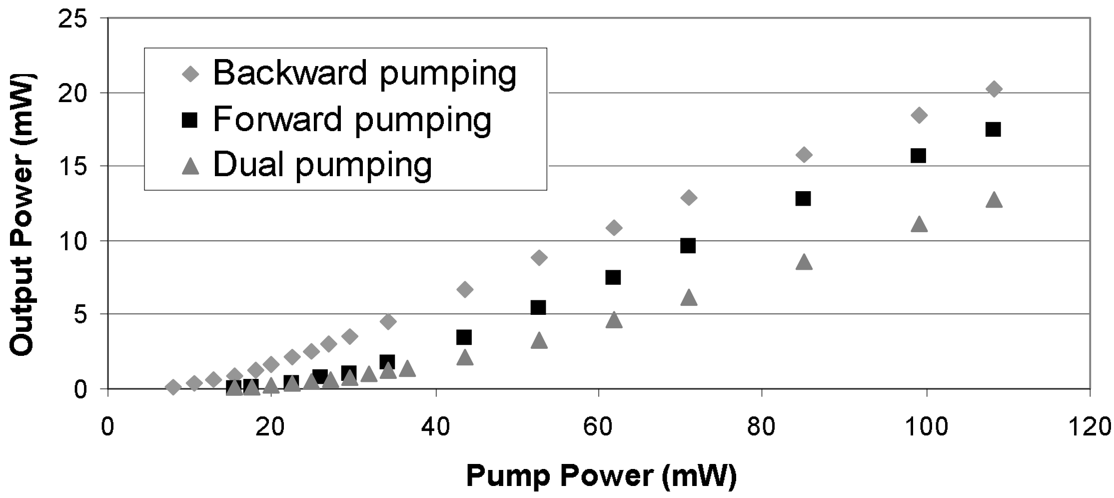


Fig. 3 Threshold and laser output characteristics of the DFB fiber laser for the 3 pumping configurations

The measured 3-dB laser linewidth behavior as a function of laser output power and pump power is shown in Figs. 4a and b respectively. In direct contrast to the threshold characteristics, the data show that the lowest linewidth operation is actually obtained with the dual pumping configuration. Indeed, for output powers up to 1 mW, the linewidth is about half that achievable with the more efficient backward pumping scheme. Over its entire output power range, the laser linewidth under dual pumping is better or comparable to that attainable with the other two pump configurations. Clearly, there are significant trade-offs between efficiency and power with linewidth and optical phase noise when designing and operating these fiber lasers.

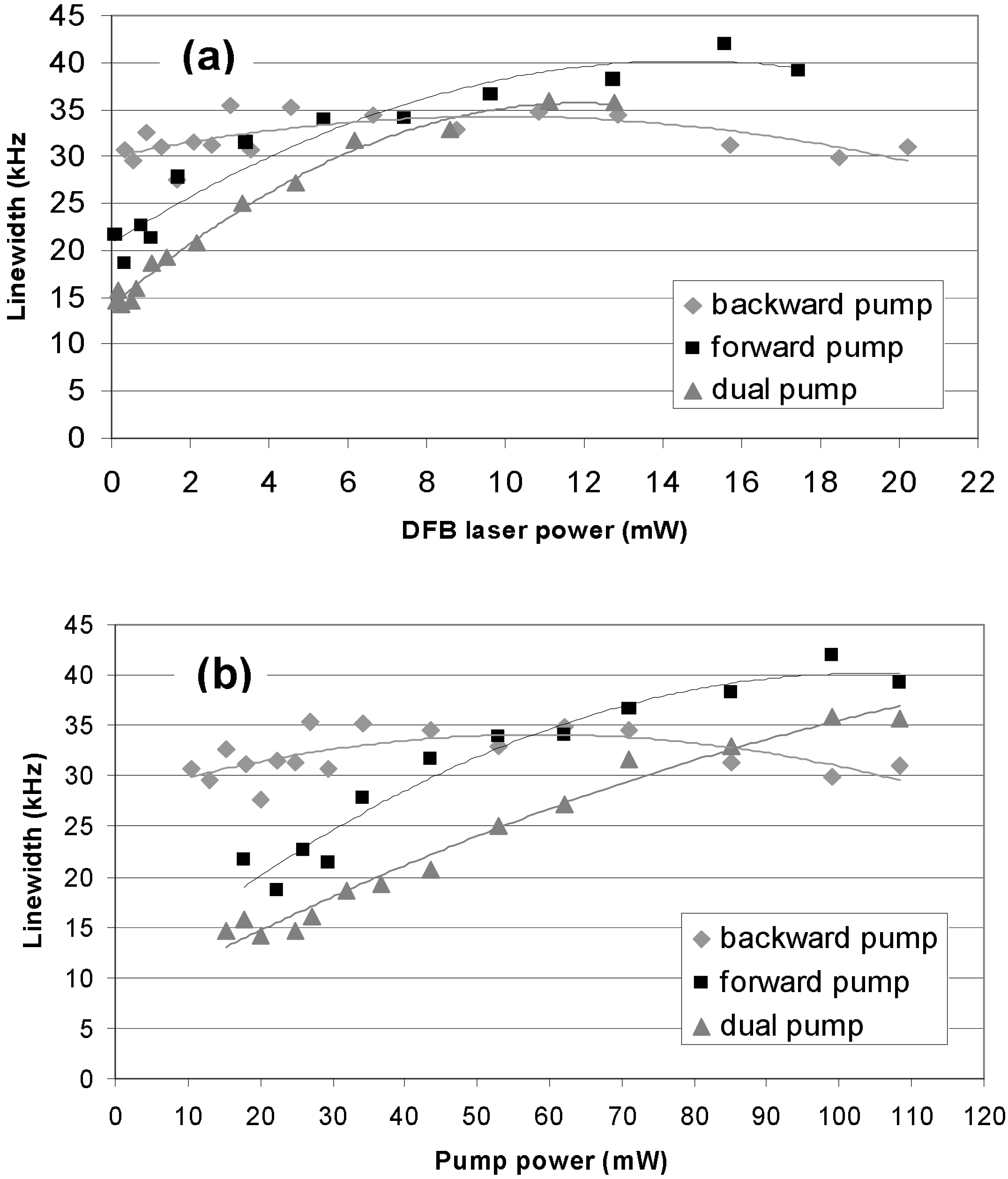


Fig. 4 Laser linewidth with (a) laser output power and (b) pump power for the 3 pumping configurations. The trendlines shown are meant simply to be a guide for the eye, and not as a rigorous fit.

The behavior of the fiber laser linewidth with power is somewhat surprising. The well-known Schawlow-Townes linewidth formula

$$\Delta \nu = \frac{2\pi h \nu \left(\Delta \nu_{cav}\right)^2}{P} \tag{1}$$

where ν is the lasing frequency, P the laser output power, and $\Delta\nu_{cav}$ the (passive) grating cavity linewidth, predicts that the laser linewidth should decrease in inverse proportion to the laser power. It may be instructive to briefly review the physical picture underlying the above formula. The origin of this linewidth is the perturbation to the laser phase caused by spontaneous emission into the laser cavity. Intuitively, it is clear that each spontaneous emission event resulting in the emission of a single photon will have less impact as the total number of photons (laser power) in the cavity gets larger. This is the physical basis for the decrease of the Schawlow-Townes linewidth with increasing laser power. In particular, note that as the laser power increases from 1 to 10 mW, the linewidth should have decreased tenfold. Instead, we observed the opposite, with the linewidth actually increasing substantially with power, particularly for the forward and dual pumping configurations. As it seems inconceivable that the spontaneous emission rate could have increased by more than 10-fold, the observations here point to a different physical origin for the linewidth. It is worth pointing out that this linewidth behavior with power is not unique to this particular laser, but has been seen elsewhere in other DBR[8] and DFB[9] fiber lasers. The issues raised by this work are thus likely to be quite general in nature.

Although the underlying reason(s) for the anomalous linewidth behavior is still unclear at this point, its dependence on pump and output power suggests that these large variations in linewidths (15 kHz to 40 kHz) are intrinsic within the laser rather than due to externally induced environmental perturbations. One would expect external perturbations (e.g. mechanical vibration) to contribute to a fixed noise floor that is independent of pump power. Similarly, the distinct variations in linewidths for the 3 different pumping configurations, but with the same pump power or output power, would tend to rule out simple causes such as pump noise or power-dependent measurement errors as plausible causes for the behavior. It is perhaps most surprising that the forward and backward pumping configurations yield significantly different linewidth behavior with pump and output power, as the grating phase shift is only located a little off-center, by 3 mm. This suggests that modifying the grating or cavity design solely to optimize for threshold and output power may incur unexpected and undesired penalties in the laser phase noise characteristics.

To investigate further, the laser lineshape was analyzed from the measured self-heterodyne rf spectrum, shown in Fig. 5. Although the spectral shape is clearly non-Lorentzian, an excellent fit could be obtained, with little deviation over a range of more than 20dB, using a convolution of a Gaussian and a Lorentzian function,

$$S(f) \propto \int dw \, \exp\left(-w^2 / w_G^2\right) \frac{1}{1 + \left(f - w\right)^2 / w_L^2} \tag{2}$$

For the particular spectrum shown, the extracted Gaussian 1/e width was w_G= 36.8 kHz, and the 3-dB width of the Lorentzian component w_L= 7.9 kHz. Interestingly, we found that, as the linewidth increases, *both* these components increase as well. It is often assumed that these components represent two distinct noise contributions. The Lorentzian component is sometimes viewed as more intrinsic by association with the Schawlow-Townes Lorentzian lineshape, and laser linewidths have been reported based on estimates of the Lorentzian component only[10]. Our findings that the Lorentzian component of the linewidth actually increases with power - contravening the Schawlow-Townes inverse power relation - render the above assumption questionable. That the extracted Lorentzian component of the linewidth might not be uniquely related to spontaneous emission should not be too unexpected. First, these Lorentzian linewidths are still orders of magnitude larger than that expected from the Schawlow-Townes spontaneous emission-induced values[6]. Secondly, while the white noise spectrum arising from spontaneous emission will yield a Lorentzian lineshape, the converse need not be strictly true. As has been pointed out by Lax, it is primarily the noise behavior in the close vicinity of the laser frequency which dictates the Lorentzian lineshape[11]. In general, the laser spectrum $S(f)$ is related to the laser frequency jitter (FM-noise) spectrum $S_F(f)$ by the relationship[12]

$$S(f) \propto F\left\{\exp\left(-4\int_0^\infty d\omega\, S_F(\omega)\,\frac{\sin^2(\omega\tau/2)}{\omega^2}\right)\right\}, \qquad (3)$$

where $F\{\ldots\}$ denotes the Fourier transform with respect to τ. Depending on the origin and behavior of $S_F(f)$, various spectral lineshapes, non-Lorentzian or pseudo-Lorentzian, would result. For example, Lorentzian-like lineshapes can also be shown to result from thermally-excited index fluctuations[13], using the derived expression for the associated optical phase noise in fibers[14]. One should therefore be cautious in assuming that any Lorentzian component extracted from the laser lineshape naturally represents a more important contribution to the phase noise than, say, the Gaussian portion.

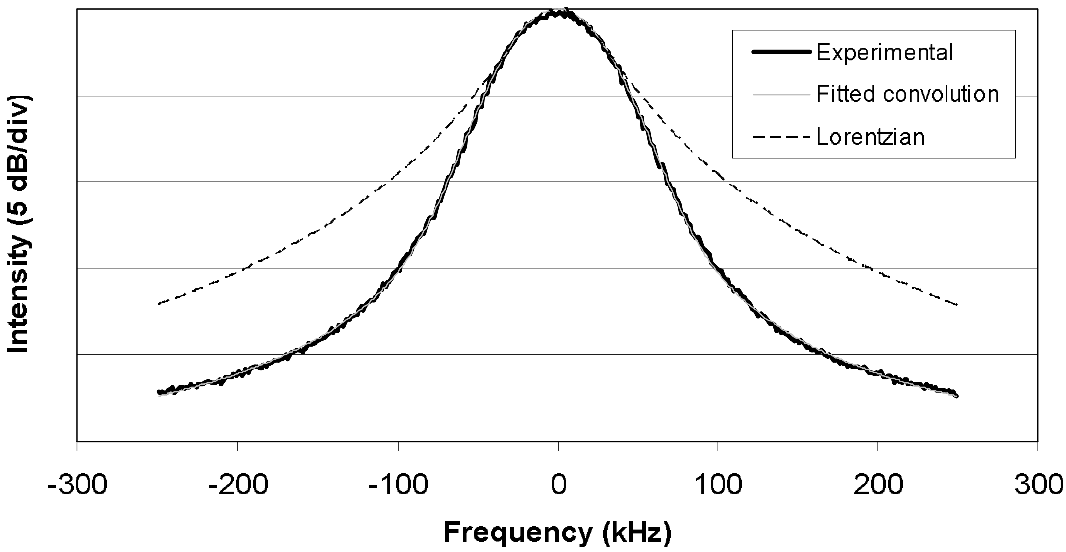


Fig. 5 Self-heterodyned rf-spectrum and its theoretical fit using a convolution of a Gaussian and Lorentzian function. A pure Lorentzian lineshape is also shown for comparison purposes. Pump power: 100mW. Resolution BW: 1 kHz; Video BW: 300 Hz.

The relatively high pump powers involved here and the strong pump absorption afforded by the Yb/Er in the fiber core - the fiber small signal absorption at 980 nm being 1200 dB/m - require us to investigate the possibility of heating/thermal effects occurring in the fiber in accounting for the anomalous laser behavior. It has been pointed out that the temperature may rise by as much as 30°C for every 10 mW/cm of absorbed pump power in doped fibers[15] with an insulating fiber cladding interface. With our pump powers of up to 100mW and more, virtually all of it absorbed over the 5 cm grating length, it is necessary to check the effectiveness of the heat sink in maintaining the temperature stability of the doped fiber. Accordingly, we measured the lasing wavelength as a function of pump power for 3 heat sink temperatures. Fig. 6 shows the results. We first note that, for a fixed pump power, the lasing wavelength increases with the heat sink temperature at the rate of 0.01 nm/°C, in line with the temperature sensitivity of the fiber grating. For a fixed heat sink temperature, however, the lasing wavelength increases only slightly with pump power, by ~20 pm as the pump increases from 15mW to 110mW. We thus infer a maximum temperature increase due to the pump of ~2°C.

As additional confirmation, numerical simulations of the heat diffusion equations for the fiber with 100mW pump absorption in the core – assuming the 125 μm fiber cladding interface is held at 20°C – also showed the resulting temperature rise in the core would be ~1°C. As the thermal contribution to optical noise in the fiber[13,14] is generally accepted to vary as T^2 (T is the temperature in Kelvin), the 2°C change incurred in the fiber over the entire laser operating range would seem to be much too small to be able to account for the large increases in obse rved linewidth, so long as the laser is properly placed in the heat sink.

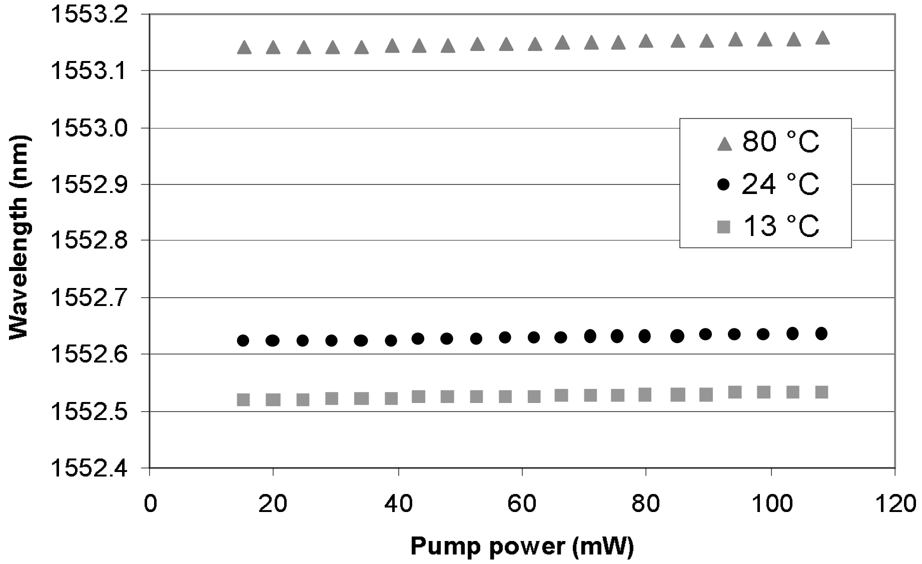


Fig. 6 Lasing wavelength with pump power for different heat sink temperatures.

Nonetheless, it has been pointed out that the thermal noise contribution to the frequency stability of these fiber lasers is not necessarily negligible[16]. To verify this, we measured the linewidth of the laser for heat sink temperatures between 10°C-80°C. The results are shown in Fig. 7, with just the two extreme temperatures for clarity of presentation. Indeed, for low pump powers, there is a marked broadening of the linewidth by ~50% when the temperature is increased from 13°C to 75°C, which is roughly in line with the expected T^2 relation for thermally-induced phase noise. These observations indicate that thermally-excited index fluctuations in the fiber laser do contribute to a substantive portion of the laser phase noise, particularly at low operating powers. However, it is interesting that at high pump powers, the linewidth proves to be virtually insensitive to temperature over the range that we were able to investigate.

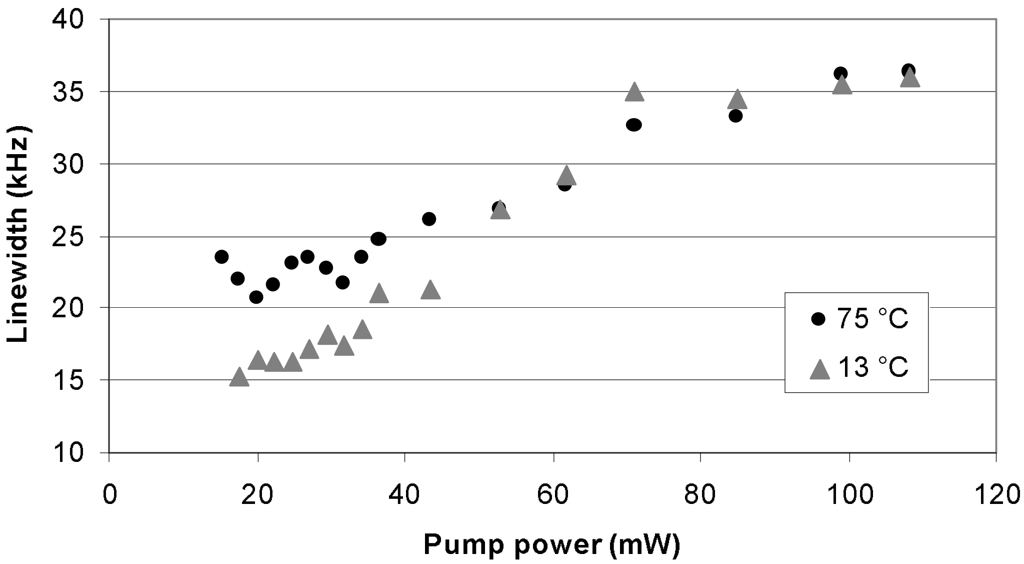


Fig. 7 Linewidth behaviour with pump power for 2 different heat sink temperatures (dual pump configuration).

4. CONCLUSION

We have presented experimental results highlighting the anomalous linewidth behavior of single frequency fiber lasers. Unusual characteristics include a tendency for the linewidth to increase considerably with pump/output power, even when mounted on a heat sink and temperature controlled to within a few ^{o}C. For the same laser cavity, the choice of pumping configuration is also found to have considerable bearing, not just on the threshold and laser efficiency, but also on the linewidths achievable. Although the cause(s) for the behavior is as yet unclear, our results strongly suggest that the anomalous linewidth behavior is an intrinsic property of the laser, and designs aimed at maximizing the laser efficiency and output power may well impact its phase noise properties in unexpected and adverse ways. One practical consequence of our findings is that the MOPA (Master Oscillator-Parametric Amplifier) configuration might actually be better suited for high power, low phase noise applications, if the degradation in signal-to-noise ratio resulting from the amplifier ASE can be tolerated.

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