ULTRASTABLE OPTICAL FREQUENCY SOURCE AND SYNTHESISER

R A Wilson, M F Lewis and P Sample,
QinetiQ, Malvern, St Andrews Rd, Malvern, Worcestershire. WR14 3PS, United Kingdom
Telephone: +44-1684-895342. Fax: +44-1684-896150. e-mail: rwilson@QinetiQ.com

Abstract: We demonstrate a 50dB improvement to the close-in phase noise spectra of diode-pumped YAG lasers and DFB laser diodes by locking the outputs to a fibre-optic delay line frequency discriminator. In addition we demonstrate a stable optical synthesiser capability with many applications in frequency standards and elsewhere.

Introduction

Frequency standards at RF invariably exploit the properties of quartz crystal resonators, which derive from the physical phenomena of piezoelectricity, low acoustic losses in dielectric crystals, and a fortunate combination of elastic constants that provides cuts of extreme temperature stability. Techniques are also well developed to multiply, divide, and combine the frequencies of quartz crystal oscillators so as to provide a digitally controlled synthesiser capability. By contrast, optical frequency standards such as lasers and gas cells derive from the physical phenomenon of discrete atomic energy levels, and so can provide extreme long-term stability *but at discrete optical frequencies*. While lasers are occasionally stabilised by external components analogous to quartz crystals, viz Fabry-Perot etalons, in this paper we describe the use of a fibre optic delay line for this purpose. Our work exploits the ultra-low loss of optical fibre to provide a high-Q optical element, which can be used to improve the spectral stability of lasers, *and also to provide an optical synthesiser and/or continuous analogue tuning capability*. The use of temperature-stable optical fibre also provides a stability comparable to that of quartz crystal oscillators at <1ppm/^{o}C, making our stable optical synthesiser suitable for use in frequency standards. Further, it provides a convenient local oscillator for measuring the spectral stability of other lasers, and a source for use in future optical vector voltmeters and network analysers for the testing of various optical components, e.g. those of interest in the telecommunications industry. It has many other potential applications in fields as diverse as spectroscopy, LIDAR and sensors.

Oscillator-Discriminator Loops

In the field of RF oscillators it is common practice to generate a stable output frequency by the use of a high-Q element, such as an LC-resonator, quartz crystal, SAW delay line or resonator, or microwave cavity. This may be an internal component of the oscillator circuit, or may act as an external frequency discriminator whose output is fed back to the oscillator so as to correct any frequency drift relative to the frequency discriminator, figure 1. The amplifier in the negative feedback loop ensures a high degree of correction, while the filter ensures stability by preventing positive feedback at any frequency with loop gain. This technique is especially useful to stabilise a high-power oscillator whose frequency drifts, e.g. with temperature. It also provides a direct measure of the spectrum of the cleaned-up output, as indicated in figure 1.

In the case of lasers, the internal high-Q element is the laser cavity, and it has been shown that the line-width of laser oscillation is inherently very narrow indeed, of order mHz [1]. However, this is rarely achieved in practice, for example the line-width of diode-pumped YAG lasers is of order 5kHz [2], while that of DFB laser diodes is typically of order of several MHz. In order to reduce the line-width of such lasers others have locked them to external high-Q elements in the form of Fabry-Perot etalons [3]. In the present work we have employed a fibre optic delay line discriminator instead operating directly at the optical frequency. This discriminator comprises a (differential) delay line and optical phase detector. The arrangement enjoys the practical advantages of compactness, ruggedness, the elimination of free-space propagation, and additional functional advantages mentioned later. In previous work we have described a superficially similar technique to implement a stable RF/microwave/mm-wave source and synthesiser [4]. This comprises a laser heterodyne source acting as the microwave VCO of figure 1, stabilised by a fibre-optic delay-line frequency-discriminator *operating at the microwave frequency.* In this scheme the frequencies of the individual lasers may drift; only their microwave difference-frequency is stabilised. By contrast, in the scheme described here the frequency of an individual laser is stabilised. The frequency control loops were analysed using well-established automatic control theory [5].

Laser Stabilisation

The configuration used to stabilise an individual laser is shown schematically in figure 2. In this apparatus the two 3dB couplers, fibre-optic delay line (delay τ), differential detectors and dc-coupled amplifier A_1, comprise the basic optical frequency discriminator, whose output may be used to monitor and measure frequency fluctuations of the laser output. The feedback loop is completed with the filter and optional differential amplifier A_2 whose second input may be used to fine-tune or frequency-modulate the laser output, as required in some applications. In this figure the second 3dB coupler, detectors, and differential amplifier A_1 comprise an optical phase detector with bipolar output of sinusoidal form, figure 3. The output of the differential amplifier is zero when the optical inputs to the second 3dB coupler are in phase or in anti-phase. A bipolar output is necessary to detect and correct frequency fluctuations of either sign. The loop is stable at points where the output of the differential amplifier is very close to zero, and the feedback negative, i.e. at alternate zero-crossing points of the differential output. Stable operation is achieved automatically when the loop is closed as the loop adjusts the laser frequency, f_L, and hence the phase shift in the fibre optic delay line, $2\pi f_L \tau$, so as to home in on the nearest stable point. Once this point is reached, the high gain of the feedback amplifier(s) ensures a high degree of correction for frequency fluctuations of the laser output, as confirmed experimentally in figures 4(a) and 4(b) for diode-pumped YAG lasers and DFB lasers respectively. For future reference, however, it should be noted that the laser/discriminator loop is stable at a comb of frequencies separated by $\Delta f=1/\tau$ which all enjoy the same phase delay, modulo 2π.

These figures were generated by monitoring the discriminator output with a low-frequency spectrum analyser, and then converting the frequency fluctuation data to a phase noise spectrum, as this is the conventional format. In each case we compare the spectra with the loop open and closed, showing a reduction of the close-in phase noise by up to 50dB. In these measurements the diode-pumped YAG laser was tuned by means of a piezoelectric element attached to the YAG crystal. The DFB laser diode was current-tuned.

We have mixed two DFB lasers to generate a microwave signal, both in their original states and in the "cleaned up" states. In the original state the RF linewidth is ~1MHz, as expected from the (combined) linewidths of the lasers. By contrast when using cleaned up DFB lasers figure 5 demonstrates the expected reduction in RF side-band levels for offsets $<\pm 1$MHz.

As noted above the stabilisation loop of figure 2 is stable at a comb of optical frequencies separated by $\Delta f=1/\tau$. In work on diode-pumped YAG lasers we have used a fibre-optic delay line of delay 1µs giving a frequency increment of 1MHz. To access these individual optical frequencies we have modified figure 2 by incorporating integrated optic phase shifter with a $\geq 2\pi$ phase shift capability, figure 6. To change from one frequency to the next we apply a sawtooth waveform to this phase modulator as shown schematically in figure 7(a) by this means the frequency is slowly swept up (or down) to the next frequency, when the phase is rapidly stepped back through 2π, too fast for the discriminator loop to respond, so the frequency stays at the new value. It is not necessary for the sloping portion of the sawtooth to be especially linear. By this means the frequency can be stepped up or down with complete reliability under manual or computer control. We have demonstrated this capability using a Lightwave Electronics diode-pumped YAG ring laser of linewidth 5kHz which is tuned via a piezoelectric element. We have stepped the (further-stabilised) output of this laser over 80MHz in 1MHz steps, and displayed the spectrum on an RF spectrum analyser by mixing the optical synthesiser output with that of a fixed frequency laser using a photodetector as mixer. The results are presented in figure 7(b), in which only every tenth spectrum is plotted to avoid the confusion of 80 overlapping spectra. It is also evident that all optical frequencies are accessible with the configuration of figure 6 by adjusting the phase to an appropriate point in the range $0\text{-}2\pi$. Furthermore a swept frequency or frequency modulation capability is accessible by the use of the phase modulator, or by the incorporation of an additional differential amplifier in the feedback loop; shown schematically in figure 6.

The synthesiser capability just described has many applications; for example as a stable programmable optical frequency source, for use in optical frequency standards. Absolute frequency control can be obtained by counting steps from the frequency of an atomic standard. A closely related application is the use of this synthesiser as a stable local oscillator whose output is mixed on a photodetector with that of a laser under test to enable optical spectral and stability measurements to be made using conventional RF/microwave test equipment.

An exciting potential application of the optical synthesiser is as the programmable optical frequency source for use in optical vector voltmeters and network analysers. The response of optical components can be assessed in amplitude and phase as a function of optical frequency, in a manner analogous to microwave test equipment. It would be quite feasible to implement an optical vector voltmeter by the use of a photodetector to measure amplitude and a phase detector of the kind shown in figure 8 to measure relative optical phase. However the sinusoidal relationship of output voltage to phase is not ideal, and such structures are prone to imperfections especially in the 50/50 coupler. While these deficiencies can be overcome by digital correction, we show in figure 9 an alternative technique to linearise the phase detector. This incorporates in one input path an electro-optic phase shifter, e.g. implemented in $LiNbO_3$. This is driven by a negative feedback loop which holds the output of the differential amplifier very close to zero. Its operation is to counteract any relative phase changes occurring between signal and reference optical inputs, its linearity deriving from the extreme linearity of the electro-optic effect. Figure 10 shows how the sinusoidal response has been linearised in an experimental set-up. With the benefit of this novel device, we can implement an optical vector voltmeter as shown in figure 8. Similarly the vector voltmeter can itself be incorporated into an optical network analyser. The operation of such in transmission and reflection is shown in figures 11(a) and 11(b), and will be self evident to those familiar with microwave measurement techniques.

The Stability of the Fibre Optic Delay Line

In the discussion above it has been assumed implicitly that the fibre optic delay line to which the laser is locked is itself stable. However, just as in the case of quartz crystals and SAW components [6], it is important to consider various sources of instability in the optical fibre delay line itself. The three most important contributions to instability in practice arise from ageing, temperature fluctuations, and 1/f noise, on time scales *of order* years, hours, and seconds respectively. Concerning temperature sensitivity, the temperature dependence of delay in single mode fibre is of order 10ppm/C. This can be reduced dramatically by appropriate cladding, and our own measurements on such temperature-compensated fibre have shown a variation of <1ppm/C, which is comparable to the behaviour of the quartz crystals used in stable oscillators. We have not yet investigated the ageing characteristics of optical fibre, but note that for the reasons just mentioned it will be important to study the ageing characteristics of temperature-compensated fibre rather than Standard Single Mode Fibre (SSMF). Concerning 1/f noise, this is the factor limiting the close-in spectrum of quartz crystal and SAW oscillators [6], so it was deemed important to investigate this aspect of optical fibre. The arrangement used was to split the output of a stable laser, pass it through two very carefully matched optical fibres of length equal to 500m and measure the spectrum of the relative output phase fluctuations using an arrangement similar to an open loop version of figure 2. The results for fibres 1 and 4 of figure 12 are most agreeable and show that the 1/f noise levels are close to our measurement capability, and result in single side-band phase noise levels <-150dBc/Hz for offsets >10kHz. It is amusing to note that if the two delays are even slightly unequal, the measurement is dominated by the spectrum of the laser, as the differential delays act as the frequency discriminator of figure 2. This is illustrated by the plot for fibres 1 and 2 in figure 12. To obtain close delay matching we used ribbon fibre containing 12 individual fibres.

Conclusion and Discussion

The development of optical fibre by the telecommunications industry has provided photonics with an optical delay line capability. In this paper we have shown that such fibre optic delay lines can be used to stabilise the output of lasers, including DFB laser diodes. The latter are especially important as they are the only means currently available to implement WDM in telecommunications. In our work on DFB laser diodes we have employed current tuning, but this is not ideal as (a) it introduces a low level of amplitude modulation, and (b) a thermal effect in the opposite direction to the electronic tuning. This limits the range of offset frequencies that can be cleaned up, as will be discussed more fully in a future publication. Here we simply note that these difficulties are absent in laser diodes tuned through the incorporation of a reverse-biased tuning section within the laser cavity [7]. The results presented here are relevant to optical frequency standards and measurement techniques [8]. However, stabilised lasers have many other applications. As an example, we have demonstrated that one of our stabilised 1.55µm DFB laser diodes can (in conjunction with an EDFA) provide an eye-safe source for a long-range LIDAR sensor [9]. Other applications of stable lasers *include* sensors, vibrometry, spectroscopy, microwave photonics [10], graviton-detection, laser cooling, and laser fusion.

References

1. T S Jaseja, A Javan and C H Townes, "Frequency Stability of He-Ne Masers and Measurements of Length" Phys Rev Letters <u>10</u> (1963) pp165-7.
2. Lightwave Electronics data sheet on Model 123 lasers.
3. M Ohtsu, M Murata and M Kourogi, "FM Noise reduction and subkilohertz linewidth of an AlGaAs laser by negative electrical feedback" IEEE QE-26 (1990) pp 231-241
4. M F Lewis and P Sample "A Discriminator controlled broad-band microwave source" MWP'97 digest pp 79-82
5. B C Kuo, "Automatic Control Systems" 7th Edition, Prentice Hall.
6. S S Elliott and R C Bray "Direct Phase Noise Measurements of SAW Resonators" Proc 1984 IEEE Ultrasonics Symposium p. 180
7. X Huang, A J Seeds, J S Roberts and A P Knights "Two-section Quantum-confined Stark effect tuned laser with uniform frequency modulation response from 30kHz to 6GHz" MWP'98 Digest (1998) pp 165-8.
8. A J Seeds, "Broadband Fibre-radio access networks", MWP' 98 Digest pp 1-4
9. R A Wilson, M F Lewis and P Sample "A Low Noise Eye-Safe Laser for use in long-range Lidar" submitted to 11th Coherent Laser Radar Conference, Malvern, UK, July 1-6 2001.

10. RA Wilson, MF Lewis & P Sample, "Developments in Coherent Beamforming for Compact Phased Array Antennas", MWP2001, Long Beach USA, Jan 2002.

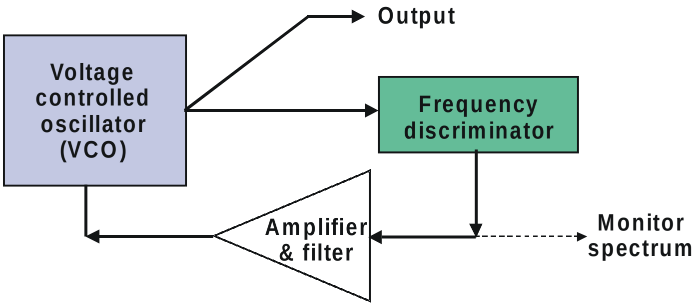


Figure 1. Schematic oscillator stabilisation using a frequency discriminator in a negative feedback loop

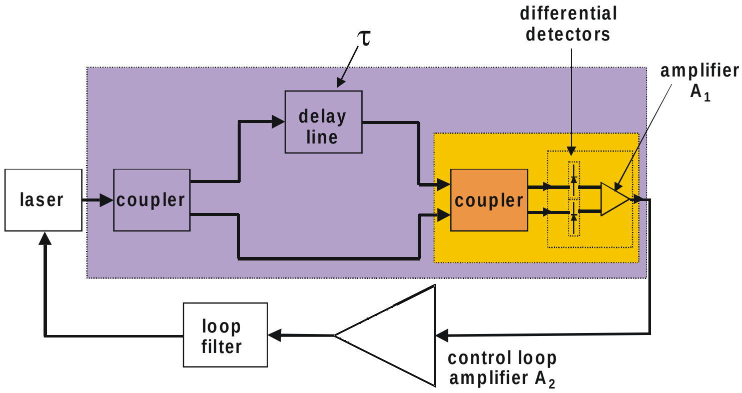


Figure 2. Schematic of laser stabilisation apparatus

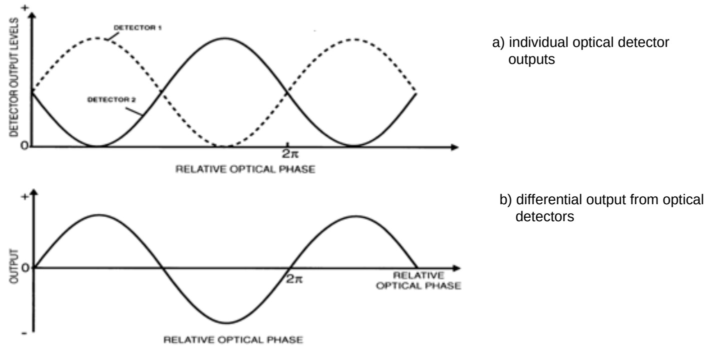
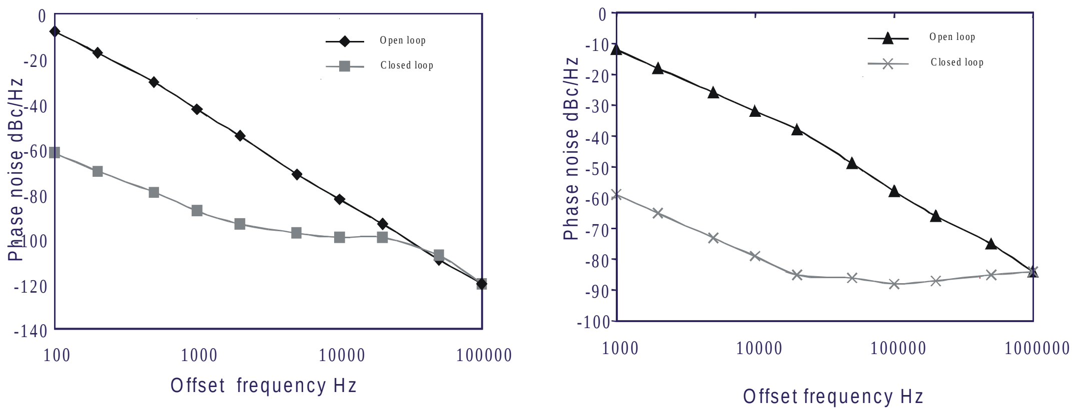


Figure 3. Optical phase detector characteristics



a) YAG b) DFB

Figure 4. Stabilised laser phase noise

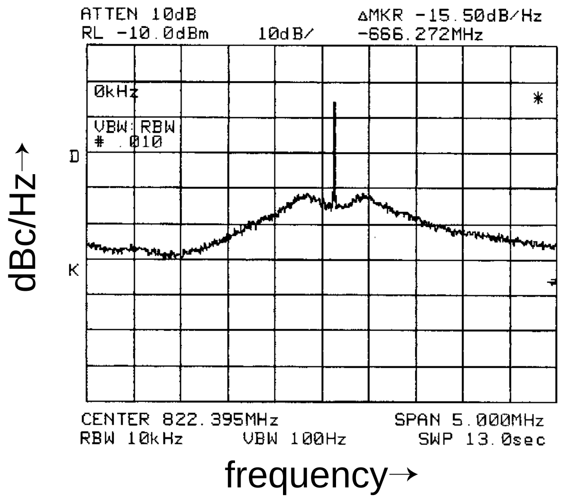


Figure 5. Spectrum of difference frequency produced by two stabilised DFB lasers

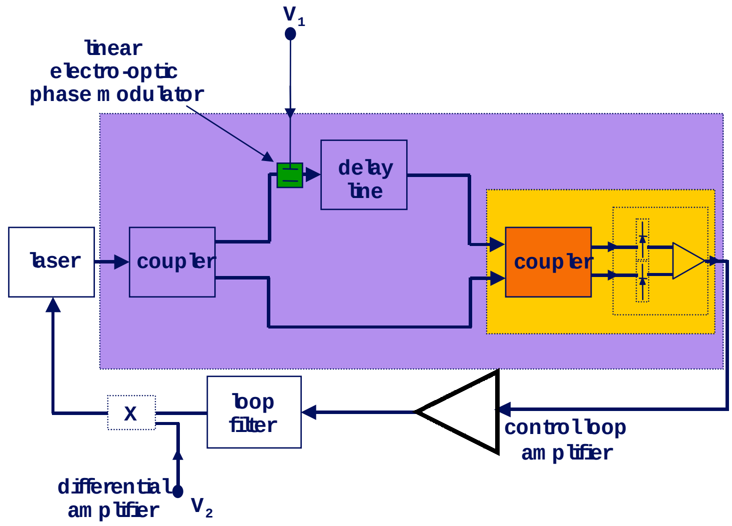
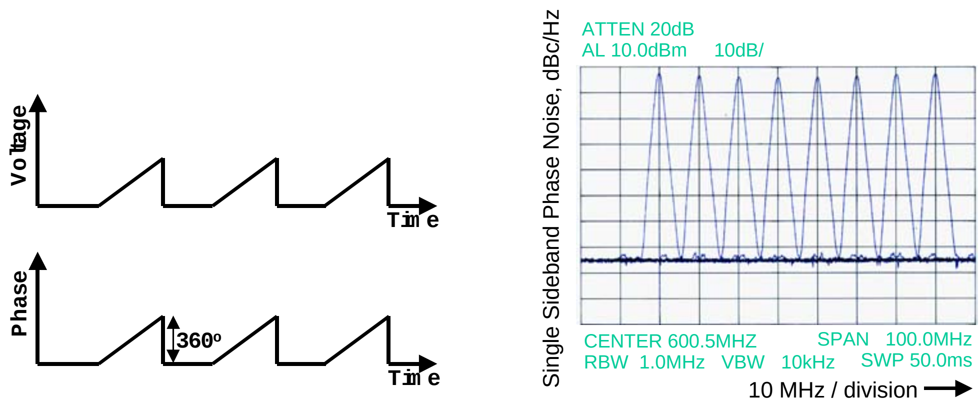


Figure 6. Schematic modification of figure 2 incorporating an optical phase modulator to give a frequency stepping capability



a) b)

Figure 7a) A sawtooth waveform applied to the phase modulator in figure 6 and b) the resulting spectra (every tenth plotted)

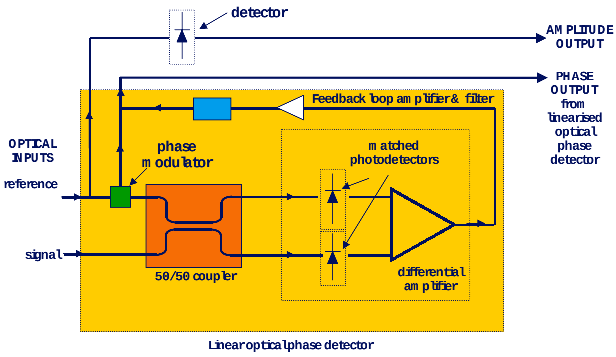
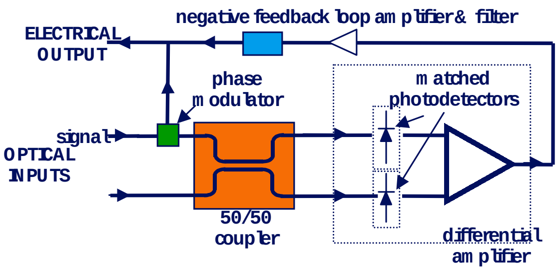


Figure 8. Schematic of an optical vector voltmeter



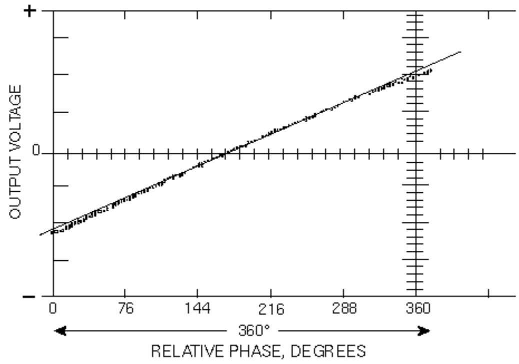
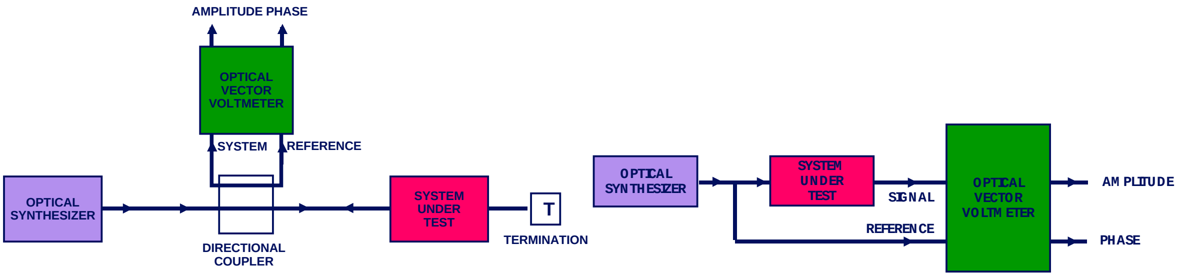


Figure 9. Schematic of a technique to linearise the optical phase detector

Figure 10. The linearised response of the optical detector



(a) reflection

(b)transmission

Figure 11. Schematics of a network analyser

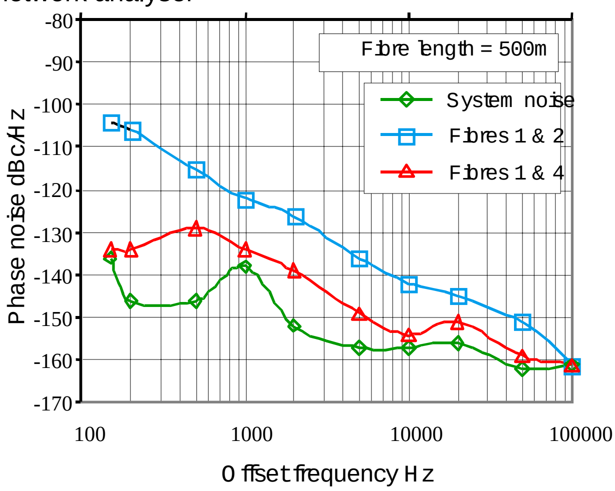


Figure 12. Phase noise produced by single mode optical fibre.