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A 1 GHz OPTICAL-DELAY-LINE OSCILLATOR DRIVEN BY A DIODE LASER

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Abstract: Experimental results are presented on a hybrid optical/electronic oscillator which uses an optical delay line to generate high spectral purity microwave signals. At Fourier frequencies above 10 kHz, the single sideband (SSB) phase noise spectrum decreases as roughly $1/f^2$ attaining a value of -138 dB below the carrier in a 1 Hz bandwidth (dBc/Hz) at 20 kHz offset. The origin of this noise is in part the fundamental shot noise on the light itself, although other optical noise sources such as double Rayleigh scattering and stimulated Brillouin scattering also appear to be important under certain operating conditions. The frequency stability over several hours is dominated by changes in the fiber ambient temperature with a coefficient of about 10^{-5}/K originating mostly from changes in the fiber refractive index with temperature.

Introduction

Stable S-band and X-band oscillators play a role in numerous applications ranging from precision metrology to optical communication systems. There are several traditional methods of generating low phase noise oscillation at these frequencies. Bulk acoustic wave (BAW) oscillators, oscillating at 5 or 10 MHz can be multiplied up to GHz frequencies. Although the initial BAW oscillator may be extremely stable, the multiplication process usually adds substantial additional noise, particularly at frequencies far from the carrier, which seriously degrades the original performance of the oscillator. Surface acoustic wave (SAW) oscillators have been used to directly generate oscillation in the frequency range of 100 MHz to a few GHz with somewhat inferior close-in phase noise performance than low frequency BAW oscillators. For even higher frequencies, up to tens of GHz, dielectric resonator oscillators (DRO's) are most often used; sapphire is the dielectric material of choice for obtaining the lowest phase noise. While these methods have been, on the whole, successful, particularly in producing signals with extremely low phase noise, their lack of tunability and difficulty of fabrication limit their usefulness in many critical applications.

Recently, a novel hybrid optical/electronic approach to this problem was proposed [1, 2]. This uses an optical fiber delay line to achieve phase noise performance competitive with the best commercially available synthesizers. These optical-delay-line oscillators (ODLO's) or light-induced microwave oscillators also have a number of highly desirable features not available in other oscillators: they are highly tunable; have oscillation frequencies which can potentially range from hundreds of kHz to tens of GHz; can have moderately low phase noise; have both optical and electronic inputs and outputs facilitating their integration with other optical systems; and can be constructed with no precision components other than commercially available optical fiber. Another important aspect of these oscillators is that their phase noise performance is independent of oscillation frequency making them excellent candidates for generating microwave signals above 10 GHz. Recent experimental results for an 800 MHz oscillator [3, 4] have demonstrated a SSB phase noise of less than -140 dBc/Hz at 30 kHz frequency offset and many future improvements seem likely.

The Optical Delay Line Oscillator

The ODLO takes advantage of the extremely low loss and long delay times which can be achieved in optical fibers in order to provide the frequency discrimination necessary for low phase noise oscillation. A diagram of one of the oscillators built at NIST is shown in Figure 1. An electronic signal is first translated into amplitude modulation on an optical carrier generated by

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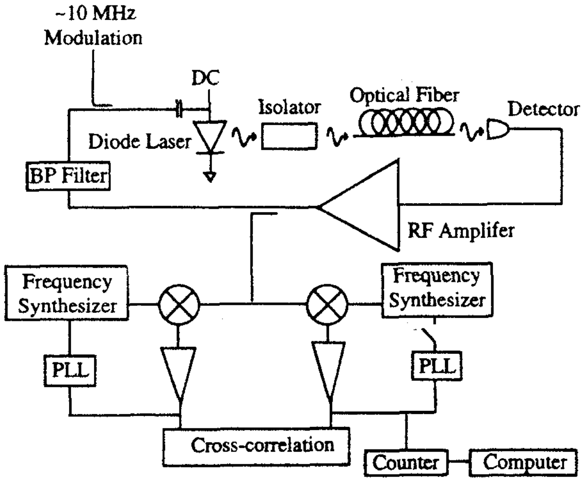

Figure 1: Experimental setup of one of the NIST optical delay line oscillators

a laser. This can be done either by directly modulating the injection current of a semiconductor laser or by using an electro-optic modulator (EOM) to amplitude modulate an externally generated cw beam. The light is passed through a long optical fiber and then sent into a high speed photodetector which converts the optical signal back into an electronic signal. The electronic signal is then amplified, filtered, and sent back into the amplitude modulator. This feedback loop defines RF "modes" which satisfy the condition that the roundtrip phase shift through the loop is a multiple of 2π. For a fiber length of 1 km, these modes are spaced by about 200 kHz.

The transfer of RF modulation into amplitude modulated light and then back into a RF signal usually involves some loss of RF power making the loop gain substantially less than unity. However, as the amplifier gain is increased one of the modes will eventually reach threshold when the loop gain is equal to unity and will start to oscillate. Which mode oscillates depends on the tuning of the RF filter. The filter gain profile acts very much like the wavelength-dependent gain provided by an atomic transition in a laser. Assuming saturation properties analogous to homogeneous broadening in a laser, when the mode at the peak of the gain profile sees unity gain, it will start to oscillate, saturating the gain, and bringing the system into equilibrium. Adjacent modes are (usually) suppressed by some large factor below the oscillating mode since the mode amplitude is enormously sensitive to the net gain in the region around threshold. How and where the gain saturation occurs depends on the exact configuration of the oscillator, as will be discussed below.

An important property of this type of oscillator is its ability to produce oscillation with low phase noise. This is true because very long delays are possible in an optical fiber with very little loss. A typical single-mode optical fiber can transmit 1.3 μ m light with as little as 0.4 dB/km of optical power loss. Since the optical power modulation is proportional to the current modulation, this corresponds to 0.8 dB/km of RF power loss intrinsic to the fiber (as opposed to $\approx$ 1000 dB/km for a delay line made of semi-rigid coaxial waveguide, for example). As a result of this low loss and long delay, the effective fractional RF energy loss per unit time in the fiber can be very small. The bandwidth of optical fiber is also extremely large, so in principle very high frequency modulation can be delayed without significant increase in the RF loss. If we assume perfectly efficient coupling of RF power into optical modulation (that is, one optical photon per electron) and then back into RF power at the detector end, then the limiting loss mechanism in the loop is the fiber loss and the Q of the cold (no gain) RF "cavity" can be as high as 10^6 at a frequency of 10 GHz. In fact, if the light could be modulated at the optical fiber bandwidth of $\approx$ 10 THz (by using two lasers at different wavelengths, for example), the intrinsic fiber Q for the ODLO could be as high as 10^9. For practical fiber lengths, the loop losses are usually dominated by coupling the RF power into and out of the optical domain, making the *actual* RF cavity Q in a real device much smaller (a few tens of thousands).

An analysis of the ODLO's RF power spectrum has been made by Yao and Maleki [3], who include amplifier thermal noise, photon shot noise, and laser noise in their model. They find that the RF power spectral density close to the oscillating mode is equal to

$$S_{rf}(f') = \frac{\delta}{(\delta/2\tau)^2 + (2\pi\tau f')^2}, \tag{1}$$

for $2\pi\tau f' \ll 1$, where f' is the frequency deviation from the nominal oscillation frequency, τ is the loop delay time and $1/\delta$ is the open-loop RF signal-to-noise ratio at the amplifier input. If the dominant noise source is assumed to be shot noise (this is often the case) then $\delta = 2eI_{ph}R/P_{rf}$, where e is the charge on an electron, I_{ph} is the DC photocurrent (a few mA), R is the amplifier input resitance, and P_{rf} is the RF power of the detector photocurrent modulation. For typical values of I_{ph} (2 mA), modulation index (0.3), and fiber length (1.5 km), this results in a single sideband phase noise of about -144 dBc/Hz at a frequency offset of 20 kHz. This is competitive with current state-of-the-art commercial oscillators. An interesting aspect of this analysis is that the phase noise does not depend on the oscillation frequency. If the mode-selection filter is moved from 1 GHz to 10 GHz or 50 GHz, the phase noise, in principle, stays the same.

Oscillator Description

We now turn to a description of the specific oscillator which has been built at NIST (Figure 1). This oscillator incorporates a number of features which make it different from the oscillator described in previous publications [3]. The main difference is that a semiconductor distributed Bragg reflector (DBR) laser, lasing at 850 nm, is used instead of a YAG laser and EOM. The laser injection current is directly modulated in order to transfer the RF signal to optical modulation. This implementation offers a number of advantages as well as disadvantages over electro-optic modulation. The most obvious advantages are compactness and lower cost. In addition, if pumped far enough above threshold, semiconductor lasers can have amplitude noise close to, or even in some cases below, the shot noise limit, which makes them ideal for use in the ODLO. One disadvantage with using diode lasers is the lower optical output power which limits the signal-to-noise ratio at the photodetector. In addition, the maximum frequency at which diode lasers can be modulated is typically somewhat lower than can be obtained in state-of-the-art EOM's.

The output from the laser was sent into 1.5 km of single-mode fiber and then into a high speed PIN photodiode. One technological issue encountered was the difficulty in obtaining high speed photodiodes which can operate with incident optical powers over a few mW. If the laser noise is close to the shot noise limit, then the signal-to-noise ratio at the photodetector improves as the optical power detected increases. As a result, in order to obtain the best phase noise performance, it is desirable to operate at the highest optical power possible. Although the laser used in the experiment was capable of generating 100 mW of optical power, it had to be used at a lower power and the light sometimes attenuated in order to avoid overloading the detector (and also, as described below, to reduce optical scattering in the fiber). Our best results were acheived with an output power of 95 mW and resulting detector DC photocurrent of 1.6 mA. The current-to-current DC efficiency from laser to photodetector was 1.2%. The low efficiency was mostly the result of an optical attenuator placed intentionally in the beam path in order to reduce the DC photocurrent to a level acceptable to the photodiode.

The output from the photodetector was sent into a series of amplification stages, the final stage having a 1 dB compression output power of 79 mW. This final stage provided the saturating element in the loop, limiting the RF power so that the power modulation on the laser was about 50% of the total power. Filtering at 1 GHz was accomplished by stub matching the 50 Ω line impedance to the laser impedance of a few ohms which provided the additional benefit of increasing the RF coupling into the laser. The tuning stub filter had a FWHM of 10 MHz about a 1.002 GHz center frequency. It is interesting to note that this impedance matching (which can also be implemented on the detector end) can actually result in RF gain [6] in the loop despite the presence of optical loss. Thus it seems possible to avoid the use of RF amplifiers altogether in this type of oscillator, drawing energy instead from the DC bias circuits of the laser and detector.

Sources of Noise

In this section, the sources of noise which affect the performance of an OLDO are reviewed. In addition to the three sources mentioned above, we found two other factors related to light scattering in the fiber which limit the performance of the oscillator under certain operating conditions. These scattering mechanisms are likely to be more important in our oscillator, which uses light at 850 nm, than in an oscillator using light at 1.3 μm or 1.5 μm.

The critical issue is the signal-to-noise ratio at the input to the RF amplifier under open-loop conditions. This signal-to-noise ratio determines not only the oscillator phase noise but also, for a given filter bandwidth, the RF power in the side modes. The three noise sources mentioned previously are thermal noise in the RF amplifier, shot noise resulting from the graininess of the laser light, and excess noise generated by the laser. When refered to the amplifier input, the noise-to-signal due to these sources is given by [4]

$$\delta = \left[4k_B T(NF) + 2eI_{ph}R + N_{RIN}I_{ph}^2 R\right]/P_{osc} \quad (2)$$

where k_B is Boltzmann's constant, T is the temperature, NF is the amplifer noise figure, and N_{RIN} is the relative intensity noise of the laser. For many semiconductor lasers operating at a few times the threshold current, and with the DC detector current into 50 Ω above a few mA, and the dominant noise source

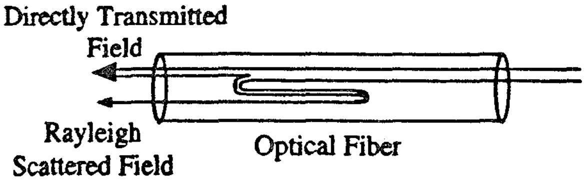

Figure 2: Double Rayleigh scattering in the optical fiber generates excess photocurrent noise when the scattered field beats with the directly transmitted field.

is shot noise. Assuming a constant modulation index on the laser light, the signal-to-noise ratio is then maximized by increasing the laser output power to its highest level and reducing the optical losses between laser and detector to a minimum. This strategy runs into two difficulties. Firstly, as mentioned above, high speed photodiodes can usually handle only limited optical power. Secondly, and more importantly, however, when high power is sent through the fiber, optical scattering mechanisms contribute additional noise and degrade the oscillator performance.

The first scattering mechanism which was found to be important in our 850 nm oscillator was stimulated Brillouin scattering (SBS). In this process, the optical field scatters off acoustic phonons in the fiber generating a backward propagating optical field red-shifted by 21 GHz from the input. The threshold input power for this process in our fiber was about 9 mW if no modulation was applied to the laser (if all of the optical power was concentrated in a single spectral region). When the optical power was increased above this level, the SBS gain in the reverse direction was larger than the fiber loss, and the counter-propagating field was amplified. When there was a significant SBS, the amplitude noise of the transmitted light increased dramatically by several orders of magnitude. It is clear, therefore, that this process imposes a limitation on the optical power which can be used in the oscillator and therefore on the maximum signal-to-noise ratio which can be achieved. Under oscillating conditions, significantly more than 9 mW of optical power could be sent through the fiber without observing the effects of SBS. This is because the laser was being modulated with a large modulation index (both AM and PM) which distributed the optical power among several sidebands and therefore reduced the power at any one frequency.

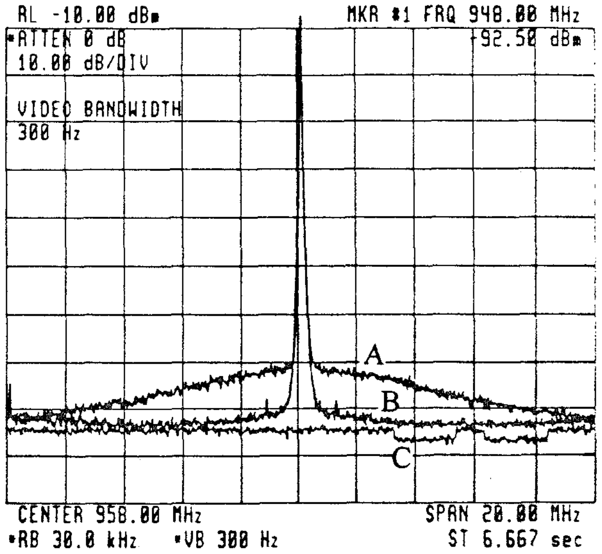

Figure 3: Excess noise about the RF carrier generated by double Rayleigh scattering. Trace A shows the increased photocurrent noise when modulation at 958 MHz is applied to the laser. Trace B is under identical conditions to A except with additional injection current modulation at 10 MHz. Trace C indicates the noise level with no RF modulation and the background amplifier noise level.

A second, and more serious problem, was that of double Rayleigh scattering (DRS) in the fiber [7]. DRS occurs because a small fraction of the optical power propagating in the fiber is Rayleigh scattered twice resulting in a weak, delayed replica copropagating with the original field in the fiber (see Figure 2). In fibers longer than the coherence length of the laser, this causes additional noise resulting from phase fluctuations of the laser. Because of the long delay, the phase noise of the scattered field is not coherent with the noise of the directly transmitted field and when the two fields are detected simultaneously on a photodetector, excess photocurrent noise is generated. When a single optical frequency is present in the fiber, this noise can be seen at low frequencies in a bandwidth roughly equal to the laser linewidth (a few MHz). If the laser is being modulated (that is, the oscillator is oscillating), AM noise is also generated around the detected RF modulation as a result of the scattered optical sideband field beating with the directly transmitted optical carrier (and vice–versa). Figure 3 shows this effect. For this measurement, the loop was open and a RF signal from a synthesizer at 958 MHz was sent into the laser injection current. The photodiode signal was then detected with a spectrum analyzer. Trace

C indicates the noise power with no modulation (the two small steps on the right indicate the background amplifier noise power). With modulation at 958 MHz applied (trace A), the noise around the carrier clearly increases as a result of the DRS.

There are several ways of dealing with this problem. Since the noise is a replica of the laser linewidth (which is true if the laser's coherence length is much shorter than the fiber length), changing the linewidth will obviously affect the noise. Reducing the linewidth will concentrate more of the noise close to the modulation signal thereby *increasing* the phase noise of the oscillator close to the carrier. On the other hand, *increasing* the laser phase noise (by adding low-frequency noise to the injection current, for example) will broaden the noise bandwidth seen in Figure 3, Trace A, thereby *reducing* the noise close to the modulation frequency and improving the oscillator performance. This was indeed the case.

A more successful solution, however, was to add additional modulation to the laser injection current at a frequency different from the oscillation frequency [8]. This spreads the optical power throughout a number of FM sidebands (separated by this new modulation frequency) while it propagates through the fiber. When the light is detected, part of the noise originally near the oscillation frequency is transferred to near the modulation sidebands. As a result, the AM noise around the original 1 GHz signal is reduced by a factor roughly equal to the number of sidebands generated by the second modulation signal. This reduction is clearly seen in Figure 3, trace B, which is taken under identical conditions as trace A, except that current modulation of 10 MHz is added to the laser injection current in addition to the 958 MHz original modulation. A reduction in the DRS amplitude noise can be clearly seen in the figure. The added phase noise on the transmitted 958 MHz signal was reduced by over an order of magnitude at a frequency 10 kHz from the carrier. Thus it seems possible to reduce, if not eliminate altogether, the effects of DRS noise using this modulation technique.

Acoustic vibrations were also found to generate oscillator noise, mostly at offset frequencies below about 1 kHz. Although we expect that compression-induced changes in the fiber refractive index are in part responsible, it was also found that the oscillator frequency was very sensitive to the position of the optical beam on the photodetector. It is thought that this sensitivity may be a result of the detector capacitance or carrier transit time changing slightly as the location of the charge-carrier generation was changed. As a result, acoustic noise changing both the detector position and also the beam pointing direction would be expected to generate phase noise in the oscillator. The use of fiber-coupled detectors might reduce the sensitivity to acoustic vibrations.

A final source of additional noise originating with the fiber results from temperature fluctuations causing the fiber length and refractive index, and therefore the oscillation frequency, to change. The temperature dependence of the refractive index for glass is about 10^{-5}/K [9] resulting in a similar coefficient for the frequency deviation of the oscillator. Thus it is expected that temperature stabilization of the fiber of the order of ≈ 100 μK will be necessary to reduce the frequency fluctuations on long time scales to below one part in 10^9.

Experimental Results

When the RF gain was increased enough to overcome the optical loss and output coupling, the system oscillated stably in a single frequency mode. A typical mode spectrum, taken with the oscillation frequency at 1 GHz, is shown in Figure 4. The power in the side modes closest to the main mode was typically between 50 and 60 dB below the main mode power (although under the optimum conditions described above, a side mode suppression of 62 dB was measured). The side mode suppression agreed reasonably well with the fundamental theoretical prediction which depends on the filter bandwidth, open loop signal-to-noise ratio and

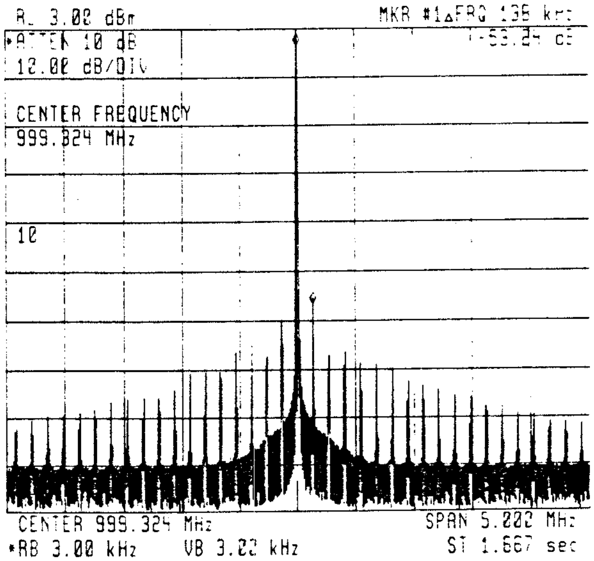

Figure 4: Mode spectrum of 1 GHz oscillator.

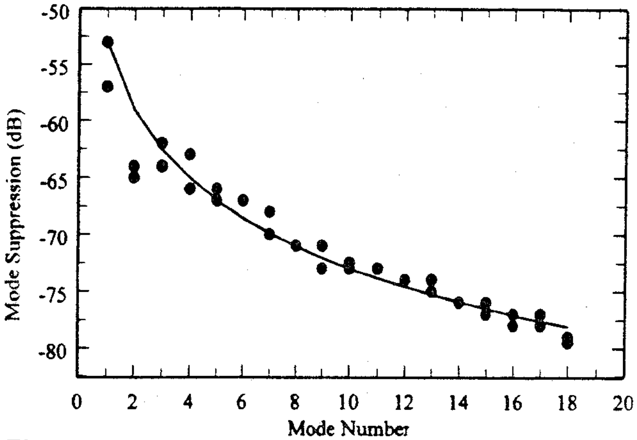

Figure 5: Side mode suppression vs. mode number for 1 GHz oscillator. The solid line indicates the theoretically predicted $1/n^2$ dependence of the side mode power on the mode number n.

mode spacing. A plot of the side-mode suppression against mode number, n, is shown in Figure 5, with the solid line indicating the theoretical $1/n^2$ dependence.

In order to accurately characterize the phase noise of the ODLO, a three-cornered-hat cross-correlation measurement was made [10]. The measurement system is shown in Figure 1 and used two frequency synthesizers as reference oscillators which were phase-locked to the OLDO at frequencies below about 100 Hz. The resulting measured ODLO-SSB phase noise spectrum, taken with 14 MHz modulation applied to the laser in order to reduce the noise from double Rayleigh scattering, is shown in Figure 6. For this measurement, 1000 averages of the cross-correlation signal were performed and the noise level calibrated with a 1 GHz noise standard [11]. The calibration was checked by frequency-modulating the ODLO with a known amplitude at 5 kHz and comparing the cross-correlation with the resulting calculated phase modulation power. Phase noise of -138 dBc/Hz at 20 kHz was measured for the 1 GHz oscillator. The plot also shows the calculated phase noise which should result from 1.6 mA of DC detector photocurrent, 50% optical intensity modulation under oscillating conditions, and open-loop detection noise at the shot noise limit. Clearly the measured noise is somewhat higher. The origin of this excess noise is likely a combination of double Rayleigh scattering and thermal noise in the RF amplifiers. The theoretical phase noise increase estimated from measurements of the DRS fiber noise (with the 14 MHz modulation applied to the laser) is also shown in the figure.

The oscillator frequency drift on longer time scales was also measured by mixing the ODLO output with the output from a frequency synthesizer and sending the resulting signal into a frequency counter, with the assumption that the crystal oscillators driving the synthesizer and counter were more stable on long time scales than the ODLO. The ODLO frequency over a period of several hours is shown in Figure 7. One data point was taken every second with a dead time of about 200 ms between measurements. A drift in the absolute frequency by 10 kHz can be seen in the figure. This drift was correlated with changes in the ambient temperature of the fiber with a measured temperature coefficient of about 10^{-5}/K which agrees well with the temperature dependence of the effective refractive index for the glass used in optical fibers [9].

Conclusions

The preliminary investigations described above and previously published results [2, 3, 4], suggest that optical delay line oscillators may be competitive alternatives to crystal and dielectric resonator oscillators if oscillation frequencies can be increased beyond 10 GHz. Their tunability and ease of construction are additional advantages. The development of these oscillators is still in its infancy and substantial room for improvement remains. Specifically, the phase noise performance can almost certainly be improved by using higher optical powers from the laser and better optical coupling from laser to detector. Diode lasers appear compatible with ODLO's and do not themselves seem to cause any fundamental problems. High performance lasers [12] having large modulation bandwidths in addition to useful output powers would be a great asset in the development of these ODLO's. To some extent, this improvement hinges on being able to find high speed photodiodes which can handle tens of mW of optical input power.

Additional reductions in the fiber-generated noise could be obtained by using optics at 1.3 μm rather than 850 nm. Although lasers at this wavelength tend to be slightly lower in optical output power, optical fibers have substantially less loss and scattering mechanisms such as stimulated Brillouin scattering and double Rayleigh scattering should be much weaker. A system with these design improvements is under construction at NIST. This system should produce even higher frequency oscillation with phase noise close to the fundamental limit set by the shot noise on the laser light.

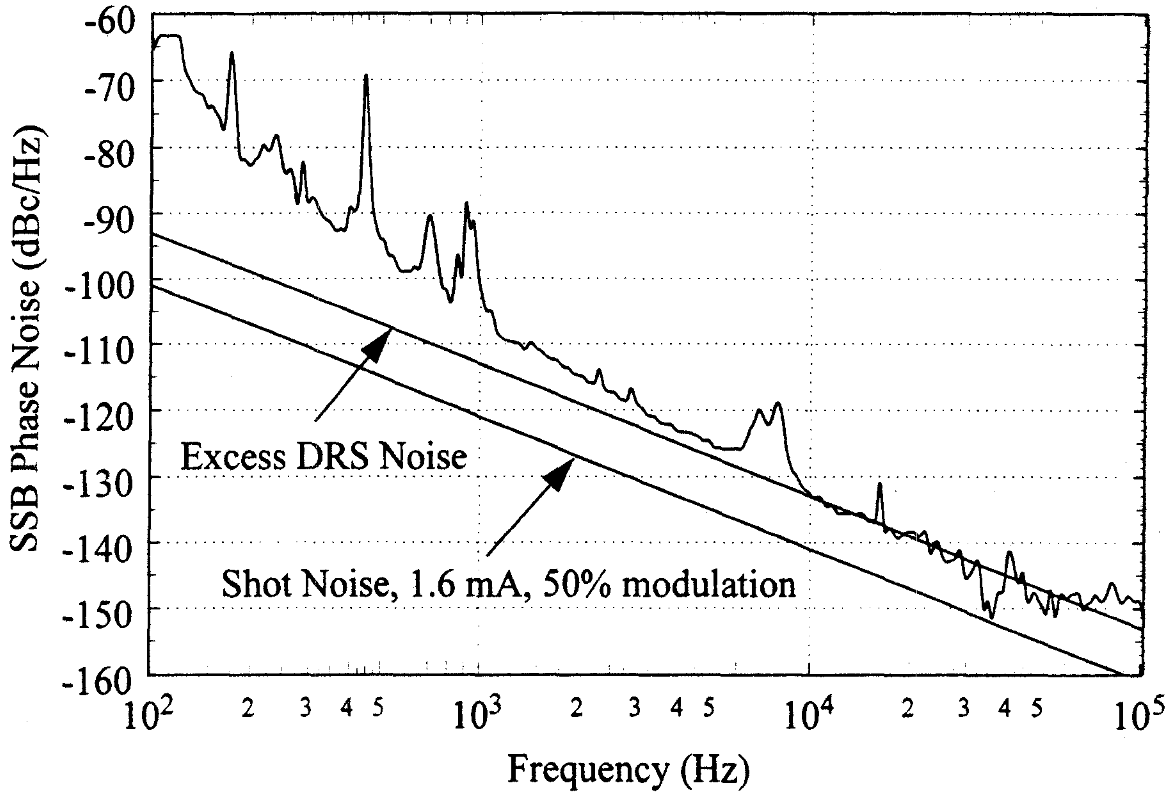

Figure 6: Single-sideband phase noise spectrum for a 1 GHz optical-delay-line oscillator. The measurement was made using the three-cornered-hat cross-correlation technique with 1000 averages. Current modulation at 14 MHz was applied to the laser to reduce the noise from double Rayleigh scattering.

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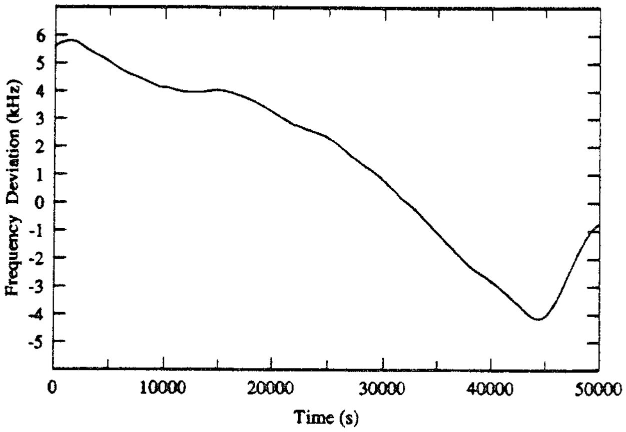

Figure 7: Optical-delay-line oscillator frequency variation over several hours. The frequency drift was correlated with the fiber ambient temperature with a coefficient of about 10^{-5}/K.

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