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Optoelectronic Microwave Oscillators Using Diode Lasers

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Diode lasers and fiber optics are increasingly finding application in solutions to a variety of technological problems. Optical communication systems, fiber sensors and medical uses are but three examples. One idea proposed recently[1] is to use optoelectronic components to generate extremely stable microwave signals at frequencies near 10 GHz. Although still in the early stages of development, these oscillators have the potential to compete with state-of-the art dielectric resonator oscillators in terms of phase stability while offering a number of desirable features including tunability, low cost and easy integration with optical systems. These optoelectronic oscillators (OEOs) have potential applications in atomic frequency standards, photonic microwave systems and optical communications.

The unique feature of this type of oscillator is the use of optical fiber rather than microwave waveguide or a dielectric resonator in the oscillator loop in order to achieve long delay times with small RF power loss. As shown in Figure 1, a microwave signal is encoded as amplitude modulation on laser light either by direct modulation of the diode laser injection current or by external electrooptic modulation. The light is then sent through the fiber and detected in a high-speed photodiode which recovers the original microwave signal with a small amount of added noise associated with the light. The photodetector output is then amplified, filtered and sent back into the light modulator forming a closed feedback loop. When the RF amplification exceeds the RF loss in the rest of the loop, oscillation occurs at a frequency determined by the roundtrip phase condition and filter center frequency. Since extremely long delays (many kilometers) with very low loss (~0.3 dB/km at a laser wavelength of 1.3 μm) are attainable using commercial optical fiber, the oscillator phase stability can be exceptional. The RF spectrum of the oscillator is given by an expression similar to the Schawlow-Townes formula for the optical spectrum of a laser oscillator. Far from the RF carrier, the phase noise is found to be proportional to the RF noise-to-signal ratio at the detector output under open loop conditions and inversely proportional to the square of the delay time[1]. The noise sources which are important in this oscillator include shot noise, excess laser noise and thermal noise at the RF amplifier input, although several other, more technical, noise processes appear also to be important. The long delays made possible by the use of optical fiber can result in very low phase noise: For reasonable operating conditions of 50 mW of optical power, 50% amplitude modulation index, shot noise limited detection and a fiber length of 10 km the SSB phase noise is of order -150 dB with respect to the carrier in a 1 Hz bandwidth (dBc/Hz) at a

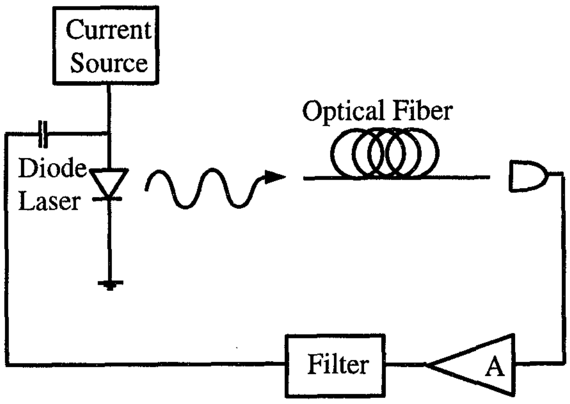

Figure 1 A typical optoelectronic oscillator

frequency offset of 1 kHz. In addition, the phase noise of the OEO is in principal independent of oscillation frequency, although a realistic upper limit of about 20 GHz is imposed primarily by how fast the optical field can be efficiently amplitude modulated and subsequently detected.

We have constructed two such oscillators at NIST, operating at frequencies between one and five gigahertz. The first uses an 850 nm distributed Bragg reflector (DBR) diode laser and 1 km of single-mode fiber. The oscillation frequency was 1.00 GHz and side-modes (due to the time delay in 1 km of fiber) spaced by 200 kHz were suppressed by over 50 dB below the main mode. The noise in this system has been fairly well characterized and, for the most part, understood. A single sideband (SSB) phase noise of -138 dBc/Hz was measured at a frequency 20 kHz from the carrier. In this frequency region, the oscillator spectrum appears to be dominated by interferometric noise generated through double-Rayleigh scattering of the light in the optical fiber[2]. Although some reduction of this interferometric noise was achieved through phase modulation techniques[3], this source still dominated at Fourier frequencies between 1 kHz and 100 kHz. On longer time scales, temperature fluctuations dominated the phase noise spectrum. The thermal coefficient of delay for standard optical fiber is about 10^{-5} per degree Celsius. Uncontrolled environmental fluctuations in the fiber temperature therefore result in changes in the oscillation frequency by several kHz.

In order to obtain improved performance, a second oscillator using 1.3 μm optics has been constructed. The longer wavelength offers a number of advantages: The fiber loss is significantly lower, the Rayleigh scattering is less and finally it is possible to buy specialized single-mode fiber at this wavelength which has a substantially reduced thermal coefficient of delay. With these improvements, some modest thermal and mechanical stabilization of the fiber and higher speed optical components, we hope to achieve oscillation above 10 GHz with a SSB phase noise of -70 dBc/Hz at 1 Hz resulting in an Allan variance of about 10^{-14} at 1 sec.

Using direct current modulation of the laser, oscillation frequencies as high as 4.3 GHz have been achieved with this 1.3 μm system. However, poor modulation efficiency of the laser limited the signal at the detector and therefore the phase noise performance and side mode suppression was not particularly good. For operation at even higher frequencies, external modulation appears to be the most promising route: Optical power levels as high as 100 mW can be modulated efficiently at frequencies up to 20 GHz using commercial Lithium Niobate modulators whereas high-speed diode lasers typically produce output powers on the order of several mW.

We will present the latest experimental results obtained with this 1.3 μm oscillator in addition to low frequency measurements of the phase noise of the 850 nm system. A configuration using two fiber loops used to further suppress the side modes[1] will also be described.

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2. S. Wu, A. Yariv, H. Blauvelt and N. Kwong, Appl. Phys. Lett., **59**, 1156 (1991).

3. A. Yariv, H. Blauvelt and S. Wu, J. Lightwave Tech., **10**, 978 (1992).