Ultra Low Phase Noise Compact-sized Optoelectronic Oscillator

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Abstract:
We demonstrate an optoelectronic oscillator (OEO) constructed with a DFB laser, a semiconductor Mach-Zehnder modulator, and a dielectric resonator based RF filter. We achieved a phase noise of -50dBc/Hz at 10Hz and -130 dBc/Hz at 10 kHz from a 10 GHz oscillation frequency, a performance comparable with that of an OEO constructed with a diode-pump YAG laser and a LiNbO3 modulator. The demonstration proves the feasibility of a high performance, low cost, and compact OEO.

1. Introduction

Optoelectronic oscillator (OEO) is capable of achieving ultra low phase noise for both microwave and optical communications [1]. The oscillation in the OEO is produced via a feedback loop which includes a modulator, an optical fiber delay, and a photodetector. We have demonstrated an OEO operating at 10 GHz with a phase noise of -140 dBc/Hz, 10 kHz from carrier [2]. This is the lowest phase noise signal from a free running oscillator operating at room temperature. However, the previous high performance OEOs were constructed with expensive and bulky diode-pumped YAG lasers, LiNbO3 modulators, and cavity RF filters. For communication, radar, and space applications, compact and low cost OEOs are preferred. We report in this paper a compact and high performance OEO constructed with an integrated module consisting of a DFB laser and a semiconductor modulator, and a dielectric resonator based RF filter. The experimental results demonstrate that low cost semiconductor lasers and modulators, together with low cost dielectric resonators, can be used to construct high performance and compact opto-electronic oscillators.

2. High-Q dielectric resonator loaded filter

The key to the low phase noise performance of an OEO is the long optical fiber loop delay. The highest spectral purity signals with the OEO are achieved with the longest fiber length [1]. Nevertheless the length of the fiber introduces a practical difficulty when the OEO operates at frequencies above a few GHz. This is because the OEO is essentially a multimode device, with its mode spacing inversely proportional to the length of the fiber. For a 1 km fiber length, the mode spacing is 200 kHz, requiring a filter with narrow enough bandwidth to select a mode for operation at a single frequency. Although a multi-loop scheme can be used for single mode selection [2], it increases the complexity and size of the OEO. In this paper, we use an ultra-narrow-bandwidth filter constructed with a dielectric resonator (DR) for single mode selection.

Dielectric resonator loaded high-Q narrow-band filters can be designed to occupy a total volume only about 5 percent of that of waveguide filter with an equivalent performance and their Q at room temperature can be as high as 10^4. In addition, the temperature coefficient of the filter is exceptionally low, down to ±1ppm/°C at room temperature [3]. We designed and fabricated such a filter by placing a 8.7mmX4mm high dielectric constant (ε_r=35) ceramic cylindrical disc at the center of an aluminum cavity with a size three times of the DR disc. Using a design tool based on the finite element method, we found that the TE_{411}

mode has the frequency of 10GHz, and more than 90% energy can be confined in the disc. To realize optimum mode matching, a tiny wire loop probe was used for both mode excitation and coupling. By carefully adjusting the wire loop, critical coupling was achieved. At critical coupling, the insertion loss was minimized and the external Q of the filter was optimized. Fig.2 shows the filter structure, as well as the TE_{411} mode field distribution in the disc and the cavity. Measured bandwidth of this filter is 2MHz at 9.56GHz with 6dB insertion loss, and a Q about 5,000. This filter allows us to use up to 6km fiber in the OEO loop for a minimum 50 dB sidemode suppression ratio, as shown in Fig. 3.

The configuration of the compact 10GHz OEO is shown in Fig. 1. The key component in the oscillator is a DFB laser integrated with a semiconductor Mach-Zehnder modulator. The measured RIN (relative intensity noise) of the laser output is -110 dBc/Hz at 10Hz and -135dBc/Hz at 10KHz, which sets the limitation of the phase noise of the OEO.

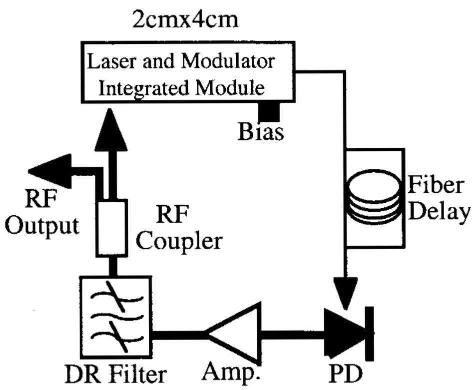

Figure 1 Configuration of compact OEO

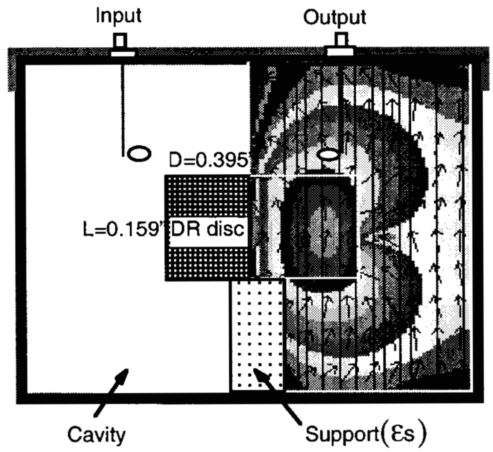

Figure 2 DR loaded filter

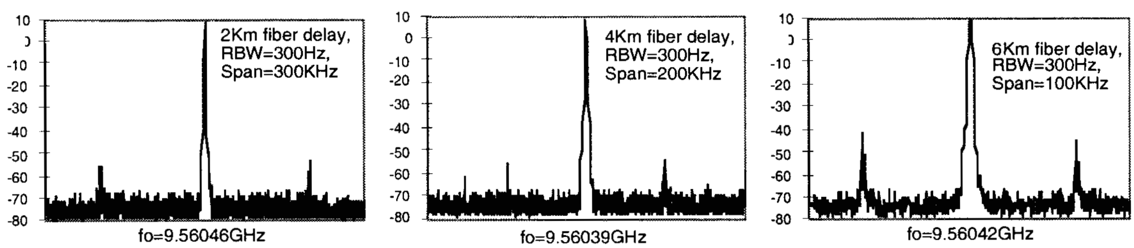

Figure 3 Comparison of oscillating modes with other side modes when 2Km, 4Km and 6Km fiber delay were used.

3. Phase noise and frequency stability

The phase noises of this compact OEO with 2Km, 4Km and 6Km loop lengths were measured by the frequency discriminator method [4], as shown in Fig.4. The 12 km fiber delay in the reference arm of the frequency discriminator converts the short-term frequency fluctuations or phase noise of a source into voltage fluctuations that can be measured by a low frequency spectrum analyzer. The phase shifter in the setup is used to keep LO and RF inputs 90^0 out of phase (phase quadrature).

The measured phase noise is shown in Fig. 5. As expected, the phase noise decreases with the increase of the loop length. However, the rate of noise reduction as a function of loop length at higher offset frequencies is slower than that at lower offset frequencies, indicating that the phase noise of the OEO at higher offset frequencies is limited by the RIN where $S_\Phi(f)$ is spectral density of phase deviation, which is double value of phase noise, f is Fourier frequency or frequency from carrier, and τ is averaging time.

For a particular type of phase noise, $S_\Phi(f) = Bf^{-\beta}$, Eq.(1) can be simplified as

$$\sigma_y(\tau) = A\sqrt{B} \cdot \frac{1}{f_o} \cdot \tau^{\frac{1}{2}(\beta-3)} \qquad (2)$$

where A is a β dependent constant, f_o is oscillating frequency, and β is the gradient in the measured log-log phase noise plot shown in Fig.5, which is 8/3 in the case of 6Km loop. So the phase noise type in our OEO should be between flicker noise (f^{-3})and white frequency noise (f^{-2}), and $A\sqrt{B} = \text{constant} = 0.061$. Therefore, for this particular oscillator, Eq.(2) can be further simplified as

$$\sigma_y(\tau) = 0.061 \cdot \frac{1}{f_o} \cdot \tau^{-\frac{1}{6}} \qquad (3)$$

The calculated frequency stability (Allan deviation) vs. time is shown in Fig. 5, the short term frequency stability (less than 1 second) is about 10^{-11}.

4. Conclusion

A compact optoelectronic oscillator (OEO) constructed with a DFB laser, an integrated semiconductor Mach-Zehnder modulator, and narrow-band DR filter was developed and measured. We demonstrated a phase noise of -50dBc/Hz at 10Hz and -130dBc/Hz at 10kHz for a 9.56 GHz oscillation frequency, and a short term frequency stability of 10^{-11}. Compact millimeter frequency OEOs are currently under development.

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References:

[1] X.S. Yao and L. Maleki, "Optoelectronic microwave oscillator," J. Opt. Soc. Am. B vol. 13, pp. 1725-1735, August 1996.

[2] X.S. Yao and L. Maleki, "Ultralow phase noise dual-loop optoelectronic microwave oscillator," OFC'98 Technical digest, pp.353-354.

[3] D. Kajfez and P. Guillon, "Dielectric Resonator," Artech House 1986.

[4] Hewlett-Packard, "Phase noise characterization of microwave oscillator - frequency discriminator method," Product Note 11729C-2.

[5] J. Rutman and F. L. Walls, "Characterization of frequency stability in precision frequency sources," Proceeding of the IEEE, vol.79, No. 6, pp.952-960, June 1991.

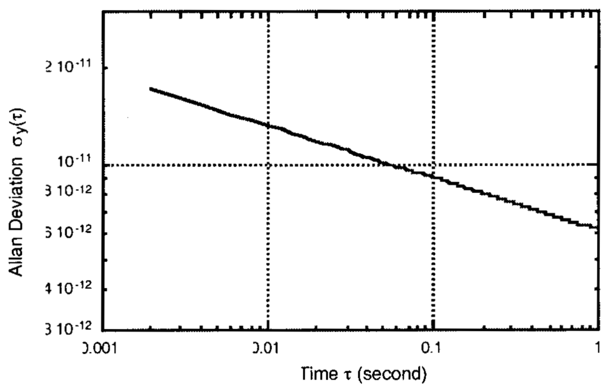

Figure 6 Calculated short term frequency stability of 6Km compact OEO from measured phase noise

noise level of the DFB laser, as mentioned above. In addition, the phase noise around sidemodes (not completely suppressed) may also contribute to the phase noise of the main oscillation mode at around 10 kHz offset frequency due to the small mode spacing (around 40 kHz).

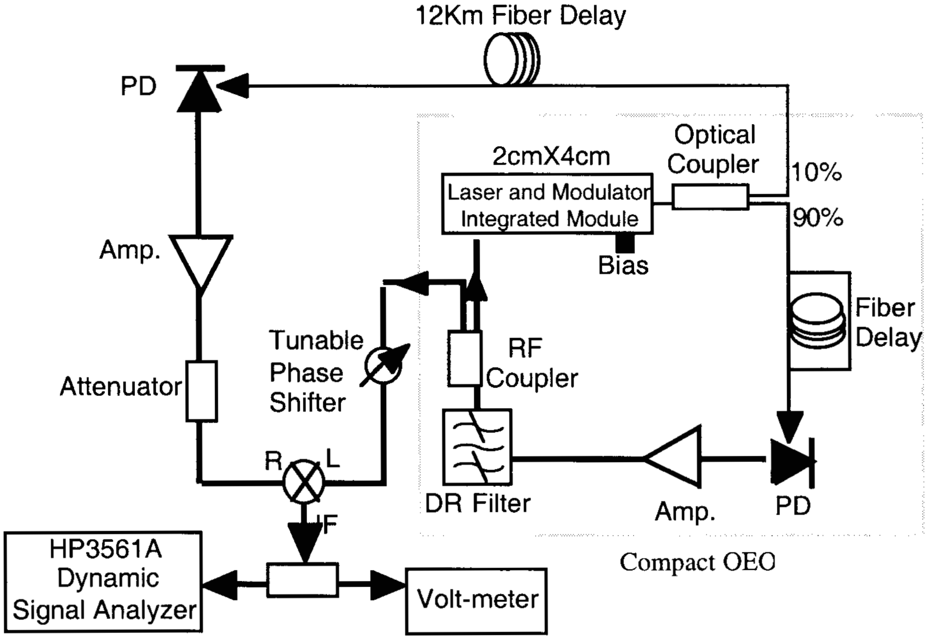

Figure 4 Phase noise measurement setup of frequency discriminator method

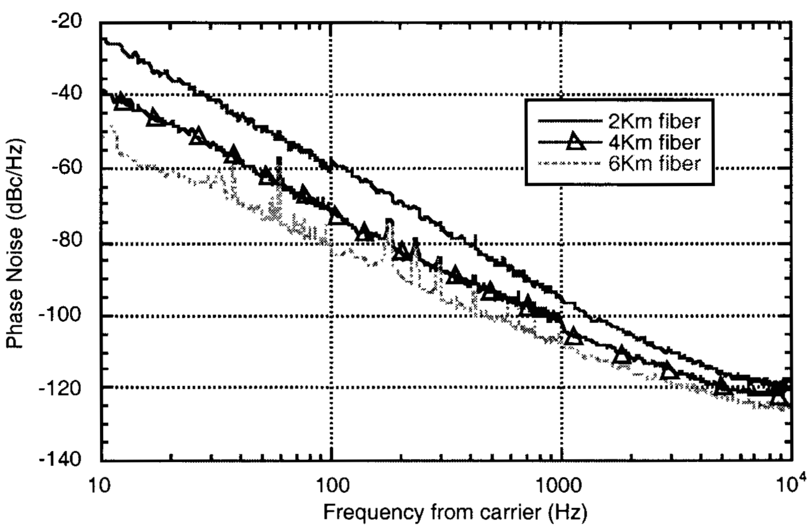

Figure 5 Measured phase noise of 2Km, 4Km and 6Km loop compact OEO

Finally, we can estimate the short term frequency stability of this compact. From the well-known theory of frequency stability [5], the two-sample variance of frequency or Allan variance, can be expressed as

$$\sigma_y^{\,2}(\tau) = 2\int_0^{\infty} \frac{\sin^4(\pi f\tau)}{(\pi f\tau)^2} S_\Phi(f)df \qquad (1)$$