# A NOVEL, HIGH FREQUENCY OPTICAL SUBCARRIER GENERATOR

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We describe an electro-optical oscillator capable of generating high stability optical signals at frequencies up to 70 GHz. We generated signals as high as 9.2 GHz at optical wavelength of 1310 nm using the oscillator, and produced a comb of stable frequencies by mode-lockins the oscillator.

in advanced photonic analog communication systems, high frequency optical subcarrier generation is essential for photonic signal up and down conversions.[1] In this paper, we report a novel optical subcarrier generator, called electro-optic (E/O) oscillator, that is capable of generating up to 70 GHz (limited by the speed of E/O modulator and photoreceiver) high stability optical subcarrier. By mode-locking the oscillator, a comb of stable high frequencies can also be generated.

The E/O oscillator[2] is described in Fig. 1. Light from one of the output ports of the modulator is detected by the photodetector and then is amplified, filtered, and fedback to the electrical input port of the modulator. If the modulator is properly biased and the open loop gain of the feedback loop is properly chosen, self electro-optic oscillation will start. Because both optical and electrical processes are involved in the oscillation, both optical and electrical signal will be generated simultaneously.

We built two such E/O oscillators using two different modulators. In the first oscillator, the Mach-Zehnder modulator has a bandwidth of 8 GHz and a half-wave voltage $V_p$ of about 17 volts. It has an internal bias control circuit that automatically sets the modulator bias at 50% of the transmission peak. The photoreceiver has a bandwidth of 12 GHz and a responsivity of about 0.35 A/W. The amplifier has a total electrical power gain of 50 dB, a bandwidth of 5 GHz centered around 8 GHz, and an output 1-dB compression of 20 dBm. The input and output impedances of all electrical components in the loop are 50 Ω. The loop length is about 9 meters.

Studies[3] have shown that depending on the biasing point of the modulator, the E/O oscillator may be bistable, oscillatory, or chaotic. However, the E/O modulator used above has a fixed bias point that cannot be adjusted. To investigate the effect of bias point on the E/O oscillator, we built another E/0 oscillator with a modulator that has an independently controlled bias electrode. However, this modulator is slower (1 GHz bandwidth) and has a half-wave voltage of about 10 volts.

With the first n/O oscillator, we demonstrated in the laboratory the first high frequency electro-optic oscillator that generated an optical subcarrier and the accompanying electric signal up to 9.2 GHz, using a diode pumped YAG laser at 1310 nm. The generated 9.2 GHz oscillation signal is shown in Fig. 2. The power of this self-oscillation measured at the electrical output port is 5.33 dBm and the bandwidth is about 100 Hz. A frequency drift of about 30 kHz was observed of the self-oscillation in a 10-minute period and is probably due to the loop length fluctuation caused by temperature and acoustic vibration. The frequency drift and bandwidth are expected to be reduced using a novel loop length stabilization technique (to be discussed elsewhere). It was interesting to observe that the oscillator self-oscillated with a 'single mode' even though no electrical filter was placed in the loop. However, multimode operation of the oscillator was also observed when the loop gain was sufficiently high.

Using the second E/O oscillator, we investigated the power spectra of the oscillator as a function of bias voltage and observed that depending on the bias voltage, the oscillator either oscillates with a single mode or multimodes of different mode spacings. As expected, these mode spacings are integers of oscillator's natural mode spacing (the inverse of the loop delay time). The bandwidth of each oscillation peak was less than 10 Hz and the center frequency fluctuation was less than 5.5 kHz/sec.

Stable multi-mode oscillation of the E/O oscillator can be realized by means of mode-locking. Similar to the case of a mode-locked laser, if a stable driving signal has a frequency that is close to an integer number of the natural mode spacing, modes with a spacing close to the driving signal frequency will be locked together in phase and the oscillator's mode spacing will be held fixed by the frequency of the driving signal, in spite of loop delay fluctuations. We were able to mode-lock the E/O oscillator with a driving signal as little as -6 dBm applied to the bias port of the E/O modulator. We confirmed the mode-locking by observing the output signal of the oscillator in the time domain on an oscilloscope: Before the oscillating modes were mode-locked, the phase of the modes fluctuated independently and the signal on the oscilloscope was a low level noise. By gradually increasing the driving power to about -6 dBm, a strong oscillatory square-like wave suddenly appeared, indicating that modes were phase-locked together.

Fig. 3a shows the power spectrum of the oscillator when it was mode-locked by a 2 dBm driving signal of 304 MHz. As can be seen, there were six modes oscillating, and the mode spacing is also 304 MHz. After examining each mode individually we found that the frequency of each mode was stabilized to the level of the driving signal and no frequency drift was observed. When the driving frequency was changed slightly, the frequency of each mode followed the change accordingly. Fig. 3b shows how the frequency of the 5th mode changed as a function of driving frequency detuning and confirms our expectation that the nth mode frequency detuning equals to n times of the driving frequency detuning. Fig. 3c shows the RF power of the 5th mode as a function of frequency detuning. It seems that the further away the mode is from its natural oscillation frequency, the lower is the oscillation RF power. It is interesting to notice that this curve is not symmetric: when the detuning frequency was less than O, the 5th mode oscillation abruptly stopped. The reason for this phenomenon is not clear to us yet.

Our analysis indicates that when $V_\pi < (\alpha\rho P_{in}/2)\pi R$ is satisfied, no amplifier is required in the feedback loop to sustain the electro-optic oscillation. in the equation, $\alpha$ and $R$ are the insertion loss (fractional) and input impedance of the modulator respectively, $\rho$ is the responsivity of the detector, and $P_{in}$ is the input optical power. For a $R$ of 50 Ω and a $(\alpha\rho P_{in}/2)$ of 10 mA, $V_\pi$ must be less than 1.57 volts. Because it is relatively easy to match the velocity of the electric driving signal over a narrow bandwidth with that of light, high frequency modulator with such a small $V_\pi$ over a narrow band maybe possible.

in summary, we generated optical subcarriers as high as 9.2 GHz using an E/O oscillator and a comb of stable frequencies by mode-locking an oscillator. Currently, we are investigating noise properties of the oscillator and developing a novel technique to stabilize the feedback loop of the oscillator.

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## REFERENCES

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## FIGURE CAPTIONS

Fig. 1 The construction of an electro-optic modulator.

Fig. 2 The generated 9.221 Hz oscillation observed on a RF spectrum analyzer.

Fig. 3 Mode-locked E/O oscillator. a) Oscillator's RF spectra measured at the optical output port using a photodetector and a spectrum analyzer. Driving signal of $f_d$ = 303.7 MHz was injected to the E/O modulator from the bias T shown in Fig. 1. Signal levels was 30 dB higher when measured at the RF output port. b) The detuning $Df_5$ of the 5th mode as a function of the detuning $Df_d$ of the driving signal. Curve-fitting yields $Df_5 = 5Df_d$. c) RF power of the 5th mode as a function of detuning.

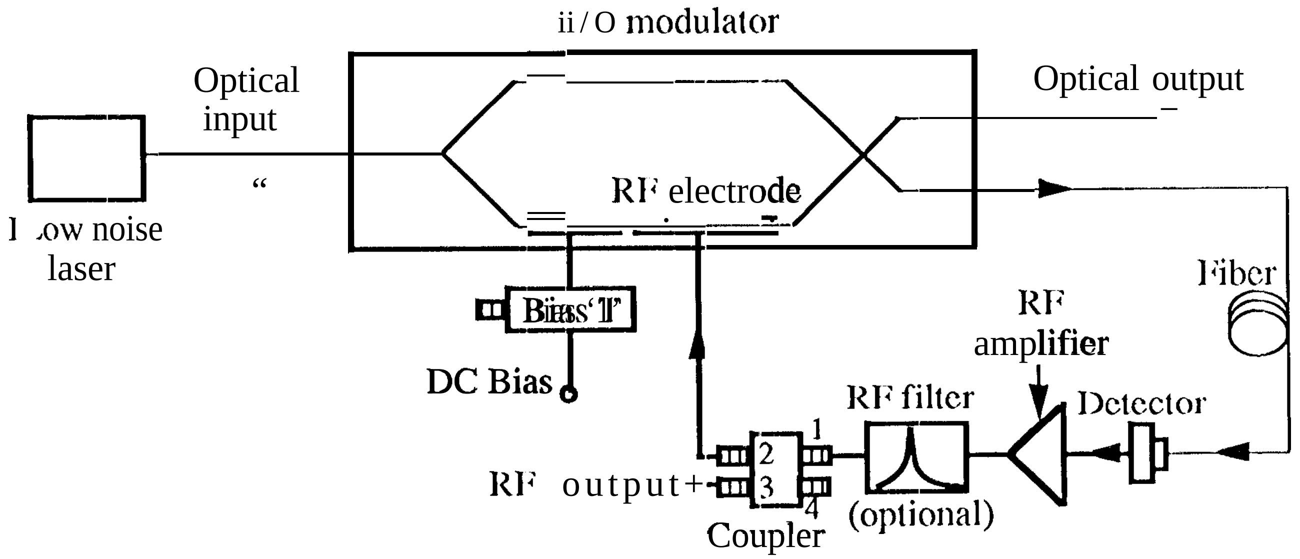

Fig. 1

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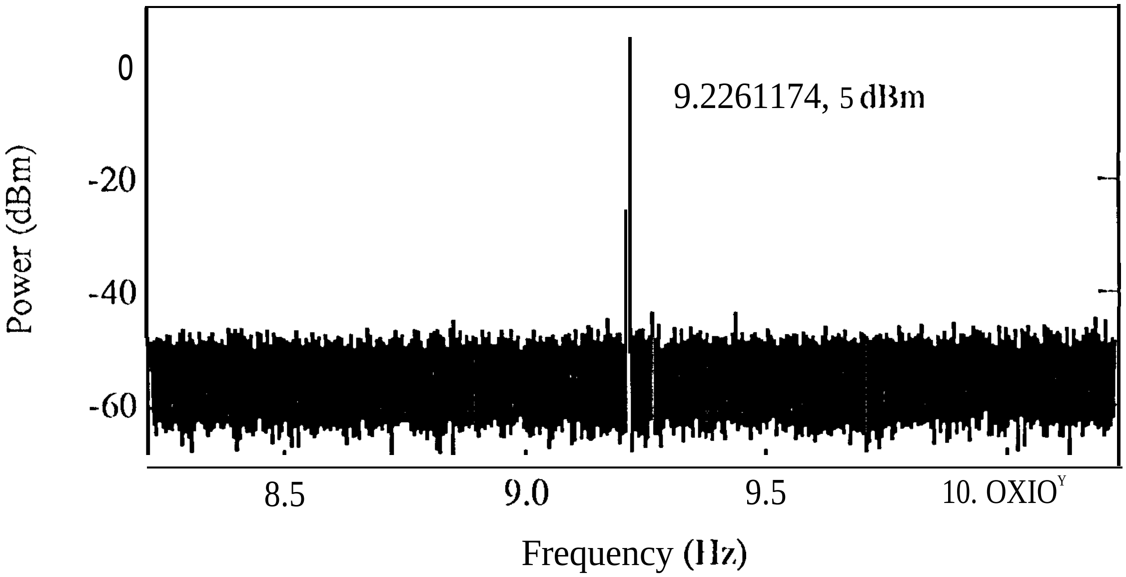

Fig. 2

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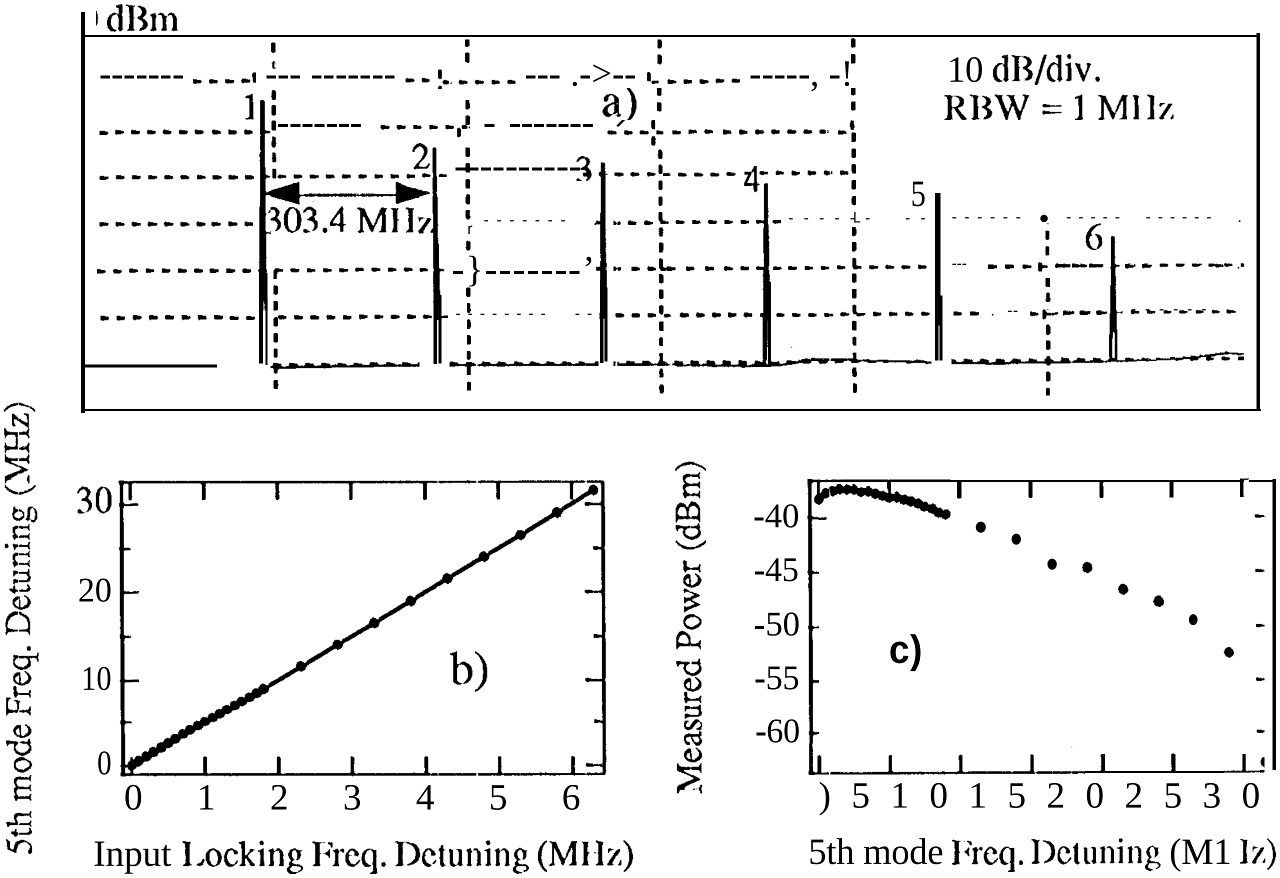

Fig. 3

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