Analyses of Short Pulse Generation Using Heterodyne Techniques

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Abstract—We have analyzed the short pulse generation using heterodyne techniques. The numerical model for semiconductor lasers under the heterodyne technique is based on the Lang's equation and has been extended in order to take into account the simultaneous injection of the multiple sidebands of the current-modulated laser. The unselected sidebands will affect the optical and RF-spectral characteristics even when the semiconductor laser is locked to the target sidebands.

Key Notes—Optical Signal Generation, Heterodyne

I. INTRODUCTION

A number of techniques for the generation, modulation, and distribution of millimeter-wave modulated optical carriers for fiber-wireless systems have been developed [1]. Optical millimeter-wave generated, in particular, has been attracting much attention in applications for broadband wireless systems, coherent multi-frequency optical communications and optical beam forming because of its flexibility in generating various frequencies. Optical sideband injection locking is one technique for its implementation. When a semiconductor laser (Master Laser) is current-modulated, it is simultaneously intensity-modulated and frequency modulated due to its frequency chirp, so that it produces a broad sideband in optical spectrum. The millimeter-wave signals can be obtained when two slave lasers are injection-locked to two different target sidebands of the master laser. When CW (Continuous Waveform) light from the master laser is injected into the slave laser, the slave laser typically shows the distinguishable spectral behaviors. And this heterodyne technique can generate GHz signal

II. RELATED WORK

A. Intensity modulation Direction detection technique

Fiber-optic microwave and millimeter-wave links which are subject to a still increasing interest can be implemented either by the use of direct detection techniques or heterodyne detection techniques. Many such links have been proposed, analyzed, and experimented. In the direct detection, the millimeter-wave signal is intensity modulated onto the optical carrier from a laser. The optical signal is then transmitted through the optical fiber, and the millimeter-wave signal is recovered by direct detection in a photodiode. In the remote heterodyne detection links, two phase correlated optical carriers are generated in a dual-frequency laser transmitter with a frequency offset the same as to the desired millimeter-wave frequency. Further, one of the optical carriers is modulated by the information to be contained in the millimeter-wave signal. Both optical signals are then transmitted through the optical fiber, and the millimeter-wave signal is generated by heterodyning the two optical signals in a photodiode. In both approaches the chromatic fiber dispersion becomes a limiting factor for the transmission distance when the microwave signals are in the above 20 GHz regime.

In an Intensity Modulation Direct Detection link (IMDD), the millimeter-wave signal is carried as a lower and upper sideband on the optical carrier. Due to the dispersion and the large frequency offset between the side bands and the optical carrier, the phase of each of the spectral components of the transmitted optical signal has experienced a differential change. After detection, this results in a power reduction of the recovered millimeter-signal and thereby decreasing its carrier to noise ratio (CNR). The dispersion induced CNR penalty on the recovered millimeter-wave signal with the carrier frequency is found by comparing the signal power of millimeter-wave signal which is recovered by square law detection of the optical signal. Power shift of millimeter-wave signal is characterized by function of fiber distance due to the chromatic dispersion effect in fiber. IM-DD link and shift of optical spectrum by external modulation technique is shown in Fig. 1. Power shift is induced by a dispersion limited fiber length and is represented as follows [2].

$$P_c = \cos\left[\left(\frac{\lambda L D}{c}\right)\lambda^2 f_{MMW}^2\right] \qquad (1)$$

where f_{MMW} denotes the RF offset frequency from the optical carrier, λ is the optical wavelength, L is the length of fiber, D is the chromatic dispersion parameter and c is the speed of light in vacuum. As shown in Fig. 2,

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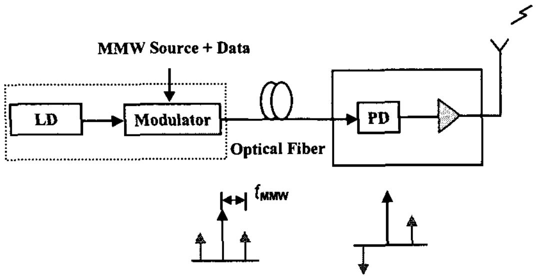
for a millimeter-wave of 30 GHz and 60 GHz, the dispersion results in a significant decrease of the CNR as the transmission distance is increased. CNR penalty is defined as follows.

$$CNR_{penalty} = 10\log\left[\frac{P_{c_{without\ dispersion}}}{P_{c_{with\ dispersion}}}\right] \tag{2}$$

This penalty limits the obtainable transmission in IM-DD fiber-optic millimeter-wave links. A complete extinction of the recovered millimeter-wave carrier occurs when the lower and upper sidebands are out of phase. The millimeter-wave carrier at 30 GHz is transmitted on an optical carrier at a wavelength of 1550 nm over a standard single-mode fiber with a chromatic dispersion of 17 ps/km·nm, large CNR penalty occurs for a transmission distance of 4 km. Furthermore, shown in Fig. 2, it is seen that the dispersion effect exhibits a cyclic behavior. The period length is found from the following equation [2].

$$\Delta L = \frac{c}{D\lambda^2 f_{MMW}^2} \tag{3}$$

The dependence of transmission of distance on chromatic fiber dispersion and millimeter-wave frequency can be estimated above equation. An increase in either dispersion or carrier frequency, therefore, significantly limits the obtainable transmission distance.



LD : Laser Diode, PD : Photo Diode

Fig. 1 Optical spectrum shift and IM-DD link using external modulation method

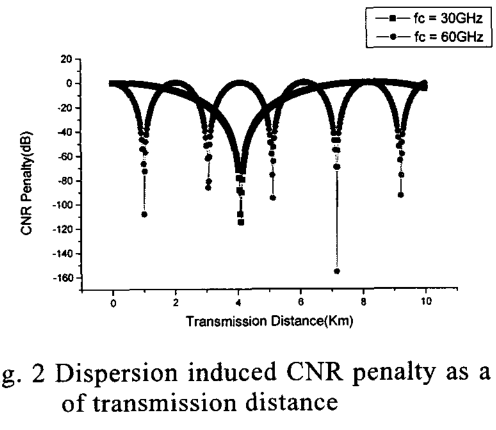


Fig. 2 Dispersion induced CNR penalty as a function of transmission distance

B. 2-Side Band Modulation Method

The dual-electrode MZM can be modeled as two phase modulators in parallel, where the amplitudes of the RF drive signals applied to each electrode are equal. A continuous-wave signal from a laser with amplitude A and frequency f_c is externally modulated by an RF signal with peak-to-peak amplitude $2V_{ac}$ and frequency f_{rf}, which is split and applied to drive electrode. A phase difference of θ can exist between each drive electrode. If the modulator has a dc-bias voltage of V_{dc} on one electrode while the other dc terminal is grounded, then the output optical field is represented as follows [3].

$$E_{out}(t) = E_{in}(t)\cos\left(\frac{\lambda}{2}\frac{V_{mod}(t)}{V_\pi}\right) \tag{4}$$

where $E_{in}(t)$ in the amplitude of input optical source is injected into modulator, and $V_{mod}(t)$ is a voltage to bias modulator. V_π is the switching voltage of the MZM. In the case of $V_{mod}(t) = V_\pi(1+\varepsilon) + \alpha V_\pi \cos(\omega t)$ output field of modulator is described as follows.

$$E_{out}(t) = \cos\left(\frac{\pi}{2}\left[(1+\varepsilon) + \alpha\cos(\omega t)\right]\right)\cos(\Omega t) \tag{5}$$

Where, α is the normalized amplitude of the drive signal, ε is the normalized bias and Ω is the optical carrier frequency. This equation can be expressed by a series of first order of Bessel functions as follows.

$$\begin{aligned} E_{out} &= \frac{1}{2}J_0\left(\alpha\frac{\pi}{2}\right)\cos\left(\frac{\pi}{2}(1+\varepsilon)\right) \\ &-\frac{1}{2}J_1\left(\alpha\frac{\pi}{2}\right)\sin\left(\frac{\pi}{2}(1+\varepsilon)\right)\cos(\Omega t \pm \omega t) \\ &+\frac{1}{2}J_2\left(\alpha\frac{\pi}{2}\right)\cos\left(\frac{\pi}{2}(1+\varepsilon)\right)\cos(\Omega t \pm 2\omega t) \\ &-\frac{1}{2}J_3\left(\alpha\frac{\pi}{2}\right)\sin\left(\frac{\pi}{2}(1+\varepsilon)\right)\cos(\Omega t \pm 3\omega t) \end{aligned} \tag{6}$$

where, J_0 and J_1 are the zero and first-order Bessel functions, respectively. When ε is "0", and dc component is V_π and center carrier components disappear. A power spectrum consists of an optical carrier at ω and 3ω, with DSB modulation showing components at ω and 3ω. ($\Omega \pm \omega$) component is mainly shown in spectrum. We can obtain 2ω or 4ω components away from reference. The millimeter-wave signal can be obtained using an electrical VCO (Voltage Control Oscillator) at half frequency of the desired millimeter-wave frequency. This technique has an advantage, that is, chromatic dispersion problem does not occur compared to the intensity modulation direct detection because this technique has no center carrier components.

C. Mode locking Method

The generation of high-frequency signals using semiconductors has been attracting attentions in recent years due to its important role in high-speed optical communications and microwave photonic systems. High-frequency signals can be generated by a variety of techniques including gain switching, active mode locking, passive mode locking and hybrid mode locking of the semiconductors. Among these methods, the passive mode locking technique is particularly attractive because it can generate millimeter-wave signals at frequencies over 100 GHz without the limitations imposed by the available drive electronics. Its inherent drawbacks of large phase-noise and difficulty in synchronization with external circuits can be overcome by implementing stabilization schemes such as sub-harmonic optical or electrical injection techniques. Mode locking method is not a form of velocity in continuous wave laser but a pulse of millimeter-wave signal by fixing a phase of a variety of optical mode laser. We can obtain desired millimeter-wave signal by beating a frequency in photodiode after choosing two modes with desired frequency difference among synchronized modes. We briefly explain a heterodyning technique by using mode-locking method [4-5]. In Fig. 3, we can select desired mode by using an optical filter like Fabry-Perot filter. In general, there are two methods to implement Mode locking scheme. One is active and the other is passive mode locking method. Active mode locking method is modulated with laser gain by injecting electrical signal to laser with frequency in contrast to resonance of laser and is synchronized a phase with resonance mode of laser. In the contrary, passive mode lock method is synchronized with resonance mode in laser to meet a phase by putting saturable absorber. To generate a millimeter-wave frequency with this method, we have to make a passive mode lock laser for generating a light of desired frequency interval by controlling interval of resonance mode and situation of saturable absorber.

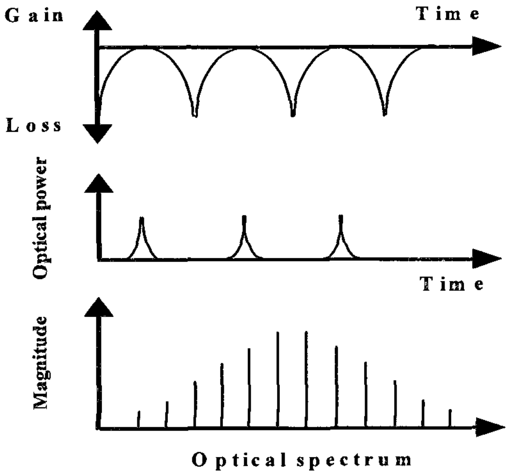


Fig. 3 Passive mode-lock method

Recently this technique was used in combination with a double modulation format for the transmission of 155 Mbit/s data signals at 62.9 GHz carrier frequency. But passive-lock technique is not stable in phase synchronization, recently synchronized harmonic frequency mode locking with laser diodes through optical pulse train injection and synchronization of sub-terahertz optical pulse train from PLL controlled pulse mode locked semiconductor laser is reported [4].

III. HETERODYNE TECHNIQUE FOR GENERATION OF SHORT PULSE

Although the direct current modulation of semiconductor lasers is simple and compact, it is not suitable to the high-speed applications. It is because the lasing frequency-shift, or chirp, during the direct current modulation combined with the fiber dispersion, causes the system performance degradation. This degradation becomes more serious when the transmission speed increases. One method of overcoming the chirp and subsequent fiber dispersion problems is to use optical injection locking (OIL). OIL provides such advantages such as the reduction of chirp, linewidth, and noise, modulation bandwidth enhancement, and other functions such as wavelength conversion, and optical generation of millimeter-wave signals. Fiber-optic transmission experiments using OIL technique has been successfully demonstrated in the modulation speed less than 500 Mbps, but not much analytical work has been done over the effect of optical injection on transmission performance. The optical injection locking technique with semiconductor laser diodes is widely used in chirp and linewidth reduction, measurement of the laser dynamics, wavelength conversion, and optical microwave generation. In particular, the optical microwave signal generation technique with injection locked lasers is very promising for many applications because it can easily produce high frequency signals with low phase noise. In the sideband injection-locking scheme, the master laser (ML) is electrically modulated and two of the resulting sidebands having the desired frequency separation are injected into two slave lasers (SLs). When these two injection-locked SLs beat each other in the photodiode (PD), the desired microwave signal is generated. Using this method, Braun *et al.* has recently reported the successful demonstration of 60 GHz beat signal generation. Our recent study on FM sideband injection locking has shown that when SLs are locked to the target sidebands of the directly modulated ML, the presence of the unselected sidebands influences the resulting microwave signals. The unselected sidebands can produce the unwanted beat signals around the desired beat signal, which degrade the overall system performance. The reduction in the incident light power helps in suppressing the unwanted beat signals, but it also reduces the locking range causing the stability problem. Figure 4 shows the optical spectra of OIL generated in difference between ML and SL. Optical spectra and comparison of wavelength by OIL scheme is shown in Fig. 4. Δλ is the value of difference between ML and SL wavelength.

Table 1 Characteristics comparison of millimeter-wave generation using heterodyne method

Method	Dispersion problem	Electrical Source (>10GHz)
SSB modulation	None	f_{MMW}
2-side band modulation	None	$f_{MMW}/2$
Mode-locking	A Little	Useless
OPLL	None	Useful (Reference OSC.)
Sideband injection locking	None	Useless

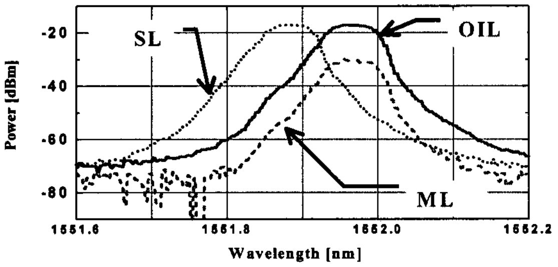


Fig. 4 Optical spectra and comparison of wavelength by heterodyne scheme

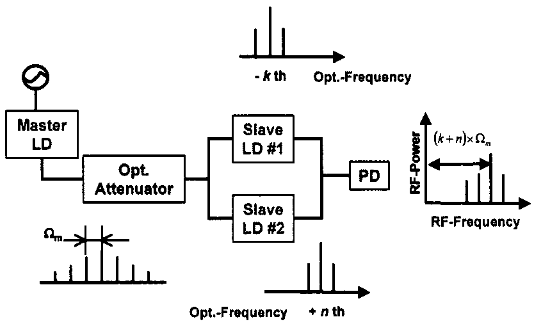


Fig. 5 Block diagram for the sidebands selection using heterodyne scheme

IV CONCLUSION

We have analyzed the heterodyne technique to generate GHz signal generation. The unselected sidebands can affect the optical and RF-spectral characteristics even when the semiconductor laser is stable-locked to the target sidebands. Due to the presence of the unselected sidebands, the unwanted powers in the optical and RF-spectra will increase with the ML power, and be combined with the fiber chromatic dispersion so that they may degrade the overall system performance.

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