IF Signal Transmission at 60 GHz-Band Using Direct Modulation of a Two-Mode Locked Fabry–Perot Slave Laser

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***Abstract*—We demonstrate the fiber transmission of an IF signal at 60 GHz-band using a two-mode injection-locked Fabry–Perot slave laser for fiber radio systems. The IF signal can be generated by the CW modulation of the slave laser without using an optical intensity-modulator. We confirm the fast response of the modulated slave laser and a 77 dB dynamic range for signal modulation against third-order distortion. The IF signals power deviation caused by fiber dispersion is also investigated.**

***Index Terms*—Fiber based millimeter-wave systems, optical signal modulation of a millimeter-wave carrier.**

I. Introduction

THE optical generation of mm-wave carriers [1]–[7] is a key technology for fiber radio systems. The optical mm-wave sources for such systems should have the following performance factors: low phase-noise characteristics of the generated carrier, tolerance against chromatic dispersion of the fiber, tunability for the carrier, and ability to work well with a low reference frequency for the carrier generation. Methods based on optical injection locking between semiconductor lasers can satisfy these performance factors. The configuration of the sources should be simple and cost-effective for constructing practical fiber-based mm-wave access systems. As an example, we obtained wide tunability of the carrier (59–64 GHz) and wide allowable detuning (8 GHz) between two lasers by using a commercially available Fabry–Perot (F–P) laser with a very low Q cavity as a slave source [6]. It is desirable for the mm-wave sources to optically modulate the carrier without using external devices for the data modulation. In this letter, therefore, we present the signal modulation of the mm-wave carrier by the direct modulation of the slave laser. The dynamic range of the signal modulation against third-order distortion is demonstrated by the F–P lasers two-tone modulation. The power deviation of the generated IF signal around 60 GHz is also investigated in order to examine the tolerance against fiber dispersion.

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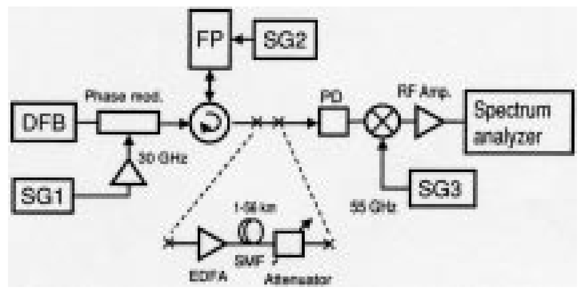

Fig. 1. Experimental setup.

II. Configuration and Experimental Results

Fig. 1 shows the experimental setup. The master laser source is a pair of sidebands generated from a 1550 nm DFB laser and a phase modulator driven by a reference signal from a signal generator (SG1). The sidebands are injected into the F–P laser through a three-port optical circulator. The mode spacing of the F–P laser is about 60 GHz. When the frequency of the DFB laser is nearly the same as the central frequency of any two modes on the F–P laser, the two modes are simultaneously locked to the frequencies of the sidebands [4], [6]. The locked modes are then coupled into a high-speed (50 GHz) PD, and the mm-wave signal is generated by the heterodyne detection.

The phase modulation (PM) or amplitude modulation (AM) of an injection-locked mode is reported in [2] and [8]. In [2], the PM of the mm-wave carrier is successfully performed by using the direct modulation of a slave laser. On the other hand, the amplitude of the locked mode is also effectively modulated with the current modulation of a slave laser when the locking bandwidth of the slave laser is very wide in comparison with the modulation frequency and the optical carrier's frequency deviation, which is induced by the modulation of the laser [8]. In the configuration of Fig. 1, two modes of the F–P laser are simultaneously locked to the sidebands from the phase modulator. Therefore, the mm-wave carrier, which is generated by the heterodyne detection in the PD, can be effectively modulated when the amplitudes of the two modes are simultaneously modulated. The direct current modulation can perform the AM of the two locked modes. In addition, a relatively high-speed AM of the modes can be expected because the employed F–P laser has a wide allowable detuning between the lasers [9]. Consequently, IF signal generation at 60 GHz-band can be expected by the simultaneous AM of the locked modes. In this configuration, the PM of the locked modes is also carried out by the current modulation. However, the PM of the carrier cannot be intrinsically

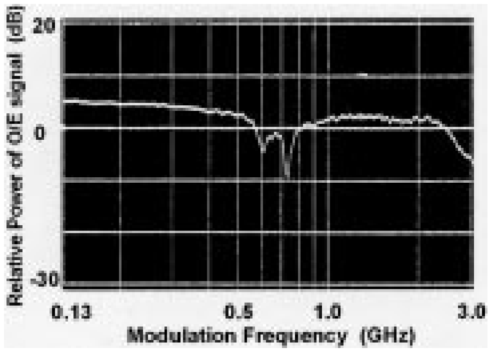

Fig. 2. Frequency response on a locked mode.

obtained at the slave laser output because the PM signals on the locked modes are cancelled out by the heterodyne detection in the PD.

Fig. 2 shows the frequency response of a locked mode selected from a circulator output by a fiber-Bragg-grating filter (0.4 nm bandwidth). In this measurement, we used an optical component analyzer (HP8703A) as a signal generator (SG2) for the current modulation. The RF power of the CW signal from the component analyzer was about 0 dBm. The injection current of the F–P laser, the driving power of the phase modulator, the reference frequency for the injection locking, and the optical sideband's power at the modulator output were 56 mA, $+13$ dBm, 30 GHz, and -15 dBm. Although there were two frequency dips, which were due to imperfections of wiring inside the F–P laser module, at 610 MHz and 730 MHz, we obtained an available response for the signal modulation when the frequency was less than 600 MHz and in the range of 800 MHz–2.3 GHz. As a result, the direct modulation of the two-mode locked F–P slave laser was very useful for fiber-based mm-wave systems because of the fast response and simple configuration of the mm-wave carrier's signal modulation [9].

Next, we tried the two-tone modulation of the F–P slave laser. The two-tone signal consisted of two CW signals (0.99 GHz and 1.00 GHz). Fig. 3 shows the relationships between the total input power of the CW signals and the output powers of the first- and the third-order components. In the measurement of these relationships, a mm-wave mixer, a signal generator (SG3) as a local signal, and an RF low-noise amplifier were used (Fig. 1). The PDs output was down-converted by the mixer and a 55 GHz CW from SG3. The gain and noise figure of the RF amplifier at 5 GHz were 31.7 dB and 2.7 dB. The dynamic range, which was determined as a ratio between the first- (4.00 GHz) and third-order (3.99 GHz) power levels, had a maximum value of 77 dB at an input power of -20 dBm, when the third-order peak just began to appear above the -124 dBm noise floor, for a 30-Hz bandwidth of the spectrum analyzer. Therefore, a sub-carrier multiplexing of data signals at 60 GHz-band can be performed by using the multi-tone modulation of the F–P laser if the frequency of the IF signal can be suitably set to avoid serious overlapping of the data spectra [10].

Finally, we examined the fiber transmission of the IF signal around the 60 GHz carrier. In this experiment, an Er-doped fiber amplifier (EDFA) with an ASE rejection filter and an optical

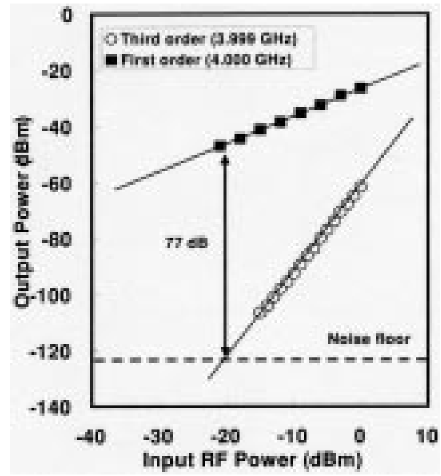

Fig. 3. Relationship between the input power of a two-tone signal and the output power of 1st or 3rd order signal.

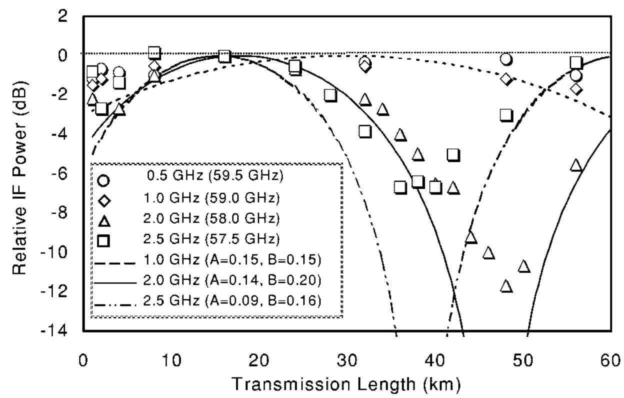

Fig. 4. Relationship between the transmission length and IF signal's power deviation.

variable attenuator were inserted into the experimental setup to feed an optically constant power into the PD (Fig. 1). The deviation of the IF signal component was investigated for the 1–56 km fiber when the IF was 0.5, 1.0, 2.0, and 2.5 GHz. The injected IF signals power into the F–P laser was fixed to -3 dBm. The RF power deviation of the IF signal was less than 2.0 dB (Fig. 4) when the IF was 0.5 and 1.0 GHz. A large penalty was observed at about 48 km and 38 km when the IF was 2.0 and 2.5 GHz. However, the transmission length for the maximum penalty was longer than the simulation result (about 30 km for the 2.0 GHz IF) from [11], and the maximum IF power was obtained at about 16 km. In [12], similar results on the dispersion effect are reported using a modulated DFB laser with frequency chirp. In the configuration shown in Fig. 1, the frequencies of the modes are injection-locked strictly. The difference in the dispersion effect between the experimental results and the simulation results arises from the mixing effect of the AM and PM of the locked modes due to the signal modulation. When the F–P laser is directly modulated without optical injection, the frequency deviation of the modes is negatively generated from the injection current modulation (red-shift). Then, the phases of the locked modes are also modulated negatively by the current modulation, while the amplitudes of the locked modes are modulated positively. Then, the electrical field of the locked

$$E_i(t) = (1 + A\cos\omega_m t)\cdot\cos(\omega_i t - B\cos\omega_m t) \quad (i = 1, 2) \quad (1)$$

and modulated modes is proportional to
where a, B, ω_i, and ω_m denote the AM index, PM index, optical angular frequency of a locked mode, and angular frequency of the IF signal. We also assume that there is no timing delay between the AM and PM on the two modes. When fiber dispersion is taken into account and $A, B < 1.0$, (1) can be expanded as follows by using transmission length L, dispersion parameter β_2, and reference optical

$$\begin{aligned} E_i(t) \approx\; & J0(B)\cos(\omega_i t + \delta_{i0} \\ & + J1(B)\cdot[\sin\{(\omega_i + \omega_m)t + \delta_{+i}\} \\ & + \sin\{(\omega_i - \omega_m)t + \delta_{-i}\}] \\ & + A\cdot J0(B)/2\cdot[\cos\{(\omega_i + \omega_m)t + \delta_{+i}\} \\ & + \cos\{(\omega_i - \omega_m)t + \delta_{-i}\}] \quad (i = 1, 2), \end{aligned} \quad (2a)$$

$$\begin{aligned} \delta_{i0} &\equiv -\beta_2(\omega_i - \omega_r)^2/2\cdot L, \\ \delta_{\pm i} &\equiv -\beta_2(\omega_i \pm \omega_m - \omega_r)^2/2\cdot L. \end{aligned} \quad (2b)$$

frequency ω_r.

The PDs current of the beat signal from the two modes is proportional to

$$I(t) = E_1(t)\cdot E_2(t). \quad (3)$$

The IF signal components $[I_{\omega LO\pm\omega m}(t)]$ in $I(t)$ become

$$\begin{aligned} I_{\omega_{LO+\omega m}}(t) \approx\; & A/4\cdot J0(B)^2\cdot f_+(t) \\ & + J0(B)J1(B)/2\cdot g_+(t)\} \end{aligned} \quad (4a)$$

$$\begin{aligned} I_{\omega_{LO-\omega m}}(t) \approx\; & A/4\cdot J0(B)^2\cdot f_-(t) \\ & + J0(B)J1(B)/2\cdot g_-(t)\} \end{aligned} \quad (4b)$$

$$\begin{aligned} f_\pm(t) \equiv\; & \cos\{(\omega_{LO} \pm \omega_m)t + \delta_{\pm 2} - \delta_{10}\} \\ & + \cos\{(\omega_{LO} \pm \omega_m)t + \delta_{20} - \delta_{\mp 1}\} \end{aligned} \quad (4c)$$

$$\begin{aligned} g_\pm(t) \equiv\; & \sin\{(\omega_{LO} \pm \omega_m)t + \delta_{\pm 2} - \delta_{10}\} \\ & - \sin\{(\omega_{LO} \pm \omega_m)t + \delta_{20} - \delta_{\mp 1}\} \end{aligned} \quad (4d)$$

where ω_{LO} is the angular frequency of the generated mm-wave carrier. The IF signals power deviation due to the dispersion can be estimated from (4a) and (4b). The relationship between L and the time averaged power of the IF signal is illustrated in Fig. 4, where $\beta_2 = -22$ ps^2/km, and the indexes of $(A, B) = (0.15, 0.15), (0.14, 0.20)$, and $(0.09, 0.16)$ for 1.0, 2.0, and 2.5 GHz IF, respectively. The value of A was estimated from the extinction ratio of the IF signal detected by a conventional speed (<10 GHz) PD. The PM index was investigated by the optical heterodyne detection between a locked mode and a single-mode reference light source. The generated beat signal from the PD was observed by a spectrum analyzer to estimate the value of B. The calculation agreed well with the experimental results. Therefore, the mixing effect of the AM and PM in the locked F–P laser can expand the allowable transmission length of the mm-wave IF signal in comparison with the IF signal transmission that is performed by combining a two-mode light source and an external modulator for the IF signal modulation.

III. Conclusion

We have demonstrated the IF signal modulation of a 60 GHz carrier by the direct modulation of a two-mode locked F–P slave laser. A simple configuration was used for the signal modulation of the generated carrier. The flat and fast response of the F–P slave laser was very useful for the generation and transmission of the up-converted IF signal to the mm-wave band. The limitation of the transmission length due to the fiber dispersion effect can be buffered via the mixing effect of the AM and PM on the injection-locked modes.

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