60 GHz Millimeter-Wave Source Using Two-Mode Injection-Locking of a Fabry–Perot Slave Laser

Masahiro Ogusu, K. Inagaki, and Y. Mizuguchi

***Abstract*—We demonstrate 60 GHz carrier generation and transmission using a two-mode injection-locked Fabry–Perot (F–P) slave laser. The relationship between the power of the generated carriers and the frequency of the reference signal for the injection-locking is also investigated. The RF power-penalty caused by fiber dispersion was within 2.0 dB when the locked modes were transmitted at distance of 0.5–48 km. Accordingly, the two-mode locked F–P laser can be used in fiber-based millimeter-wave systems.**

***Index Terms*—Fabry–Perot laser, fiber dispersion, fiber transmission of millimeter waves, injection-locking, optical generation of millimeter waves.**

I. Introduction

Wireless communication links using fiber-based millimeter-wave (mm-wave) systems are expected to support high-capacity networks in the future. One of the research areas for such systems is the optical generation of mm-wave carriers. The optical mm-wave sources of these systems should have at least the following performance for generated carriers: purity (low phase-noise), tunability, and tolerance against fiber dispersion. Methods based on the heterodyne detection of two waves in a photo detector (PD) and the optical injection locking of semiconductor laser diodes can not only achieve this performance, but can also reduce the reference frequency for the carrier generation [1]–[4]. The mm-wave sources should also have simple and cost-effective configurations to enable the construction of practical mm-wave access systems. When injection locking between lasers is adopted for a mm-wave source, an issue that becomes very important for the stability of the generated carriers is the immunity of the source against frequency detuning between the master and slave lasers [1], [4]. By using a simple Fabry–Perot (F–P) laser with a very low Q cavity as the slave source, we were able to obtain the widely allowable detuning of 8 GHz, which corresponded to the laser's thermal deviations of $\pm 0.3\,^{\circ}$C. We could also confirm a wide tunable range (59–64 GHz) without changing the temperatures or the injection currents of the lasers [4]. In addition, a configuration that uses a multimode-laser as the slave source can introduce an expansion of the frequency range for the master source [3], [4]. This wide range is cost-effective because any of a number of DFB (master) lasers can be adopted without selecting a matched pair of lasers for the injection locking.

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The authors are with ATR Adaptive Communications Research Laboratories, Kyoto 619-0288, Japan (e-mail: ogusu@acr.atr.co.jp).

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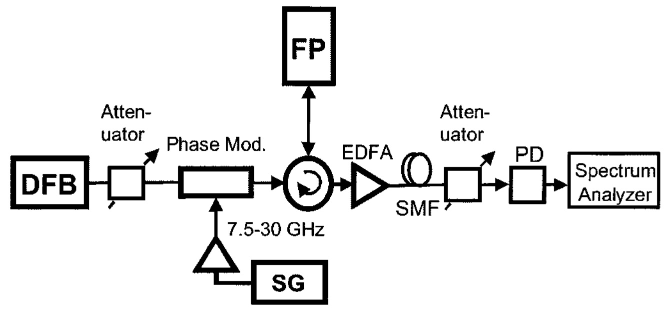

Fig. 1. Experimental setup.

In this letter, we present phase-noise characteristics of 60 GHz carriers from the above two-mode locked F–P laser and the relationship between the power of the carriers and the frequency of the reference signal for the injection-locking. The fiber transmission of the carriers in investigating the immunity against fiber dispersion is also reported.

II. Carrier Generation and Fiber Transmission

The experimental setup is shown in Fig. 1. The master laser source is a DFB laser whose spectral width is about 10 MHz. The DFB lasers output is coupled into a phase modulator via an optical attenuator. The modulator is driven by the reference signal from a signal generator. The modulator output is connected with 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 of the F–P laser, the modes are simultaneously locked to a pair of sidebands from the modulator. The locked modes are sent to a conventional single-mode fiber (SMF). An erbium-doped fiber amplifier (EDFA) is connected to the circulator output to compensate for the transmission loss of the fiber. The locked modes are then detected in a high-speed (50 GHz) PD, and the beat signal is observed with a spectrum analyzer. The temperatures of both lasers are controlled to $\pm 0.01\,^{\circ}$C; this is sufficient for the stable locking of the F–P laser.

Fig. 2 shows the optical spectrum of the circulator output when the frequency and power of the reference signal were 30 GHz and $+13$ dBm. The optical power at the modulator output was -13 dBm. The injection current of the F–P slave laser was 58 mA, which was 1.2 times larger than the threshold current. The optical gain in the slave laser was about 15 dB. The generated 60 GHz carrier and the phase-noise characteristics are shown in Fig. 3(a) and (b). The phase-noise at 100 kHz offset

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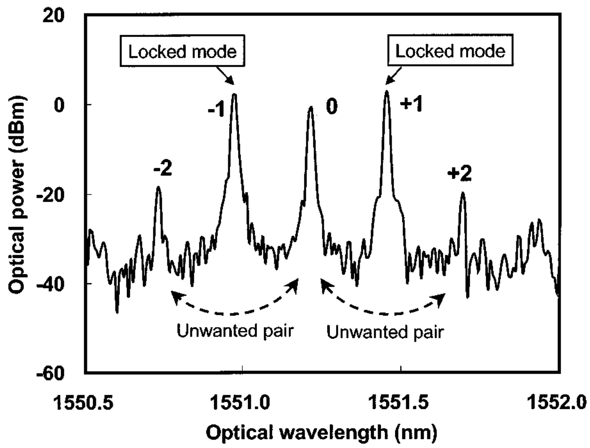

Fig. 2. Optical spectrum of a two-mode locked F–P laser.

was -92.8 dBc/Hz, which indicated only 7.5 dB degradation from the 30 GHz CW of the generator. The phase noise appeared to be large in the high frequency offset region due to the lack of the carrier's power for the phase-noise measurement because the bandwidth of the PD was about 50 GHz. The relationship between the reference frequency and the phase-noise at 100 KHz offset is shown in Fig. 3(c). The purity of the generated carriers was maintained (< -90 dBc/Hz) for the reference signal of 7.5–30 GHz CW because the phase-noise characteristics of the generator's output were improved as the frequency was lowered.

The reduction of the reference frequency was limited by the allowable detuning between the lasers. When the reference frequency was lower than 7.5 GHz, the carrier's power became unstable. In addition, the power ratio of a pair of sidebands for the injection-locking to the total power at the modulator output became small as the reference frequency was lower. In the case of the small power ratio, the F–P slave laser tended to saturate due to the optical injection of the lower order sidebands, which were not related to the two-mode injection-locking. We investigated the relationship between the power of 60 GHz carrier and the optical power at the phase modulator output when the reference frequencies are 30, 15, 10, and 7.5 GHz (Fig. 4). The optical power was controlled by the optical variable attenuator inserted at the DFB laser. The injection current of the F–P laser and the power of the reference signal were fixed to 58 mA and $+13$ dBm. It was found that the modulator output should be less than -10 dBm to avoid the FP laser's saturation.

Next, we attempted the fiber transmission of the locked modes to investigate the tolerance against fiber dispersion. Fig. 5(a) and (b) show the relationships between the transmission length of the modes and the RF power penalty of generated carriers when the optical power at the PD was fixed to -10 dBm by adjusting an optical variable attenuator inserted at the PD. The power of the reference signal and the injection current of the FP laser were 13 dBm and 58 mA. The reference frequency of 30 and 15 GHz were examined for the carrier transmission. We were able to transmit carriers over 0.5–48 km single-mode fibers although the deviation of carrier's

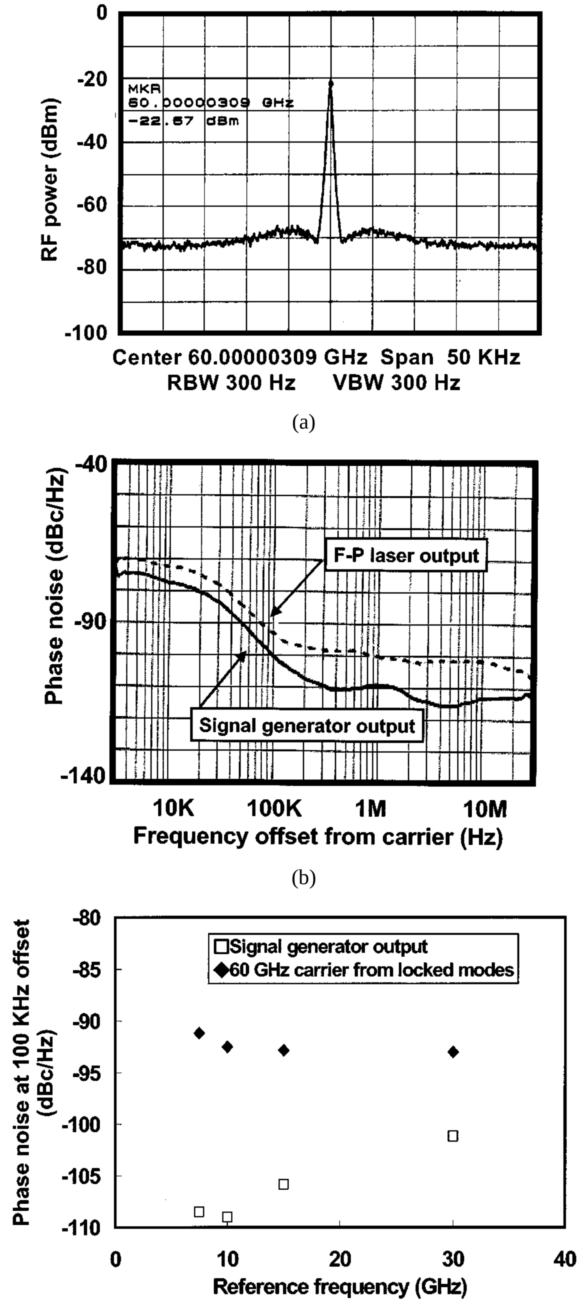

Fig. 3. (a) Generated carrier. (b) Phase-noise characteristics of 60 GHz carriers and signal generator output. (c) Phase-noise at 100 KHz offset from 60 GHz for different reference signal frequencies.

power was observed. An optical carrier from the DFB laser and the unwanted sidebands from the phase modulator were partly passed through the F–P laser (Fig. 2). These unwanted components induced the carrier's power deviation due to the fiber chromatic dispersion [5]. In the case of the 30 GHz reference signal [Fig. 5(a)], two unwanted 60 GHz beat signals, which were induced from the DFB laser's optical carrier and the $\pm$2nd sidebands at the PD, interfered with the 60 GHz carrier from the locked modes. However, the power penalty due to the dispersion was within 3.5 dB. The power penalty could be reduced within 2.0 dB when a 0.8 nm band-pass filter

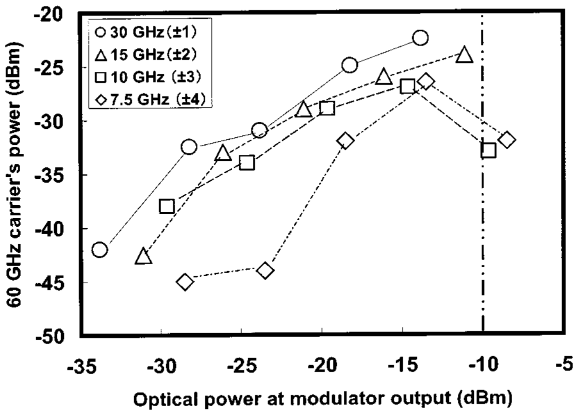

Fig. 4. Relationship between the power of 60 GHz carrier and the optical power at the modulator output.

was inserted into the circulator output to suppress the ±2nd sidebands. The power penalty's periodicity L is given by

$$L = 2\pi\{\beta_2 \omega_{RF}(\omega_{locked} - \omega_{unwanted})\}^{-1} \quad (1)$$

where β_2, ω_{RF}, ω_{locked}, and $\omega_{unwanted}$ are the group-velocity dispersion parameter of the fiber, angular frequency of the generated carrier, averaged angular frequency of the locked modes, and averaged angular frequency of a pair of optical components (zeroth and second sidebands), which generate the unwanted beat signals, respectively. The periodicity of 4 km [Fig. 5(a)] was reasonable because the result well matched equation (1), where β_2 was set to 22 ps^2/km (this is a typical value for conventional single-mode fibers) and $(\omega_{locked} - \omega_{unwanted}) \cdot (2\pi)^{-1} = 30$ GHz. When the reference frequency was 15 GHz, two unwanted 60 GHz beat signals, which were induced from two pairs of the ±first and the ±third sidebands, interfered with the carrier from the locked modes. The power penalty was about 6 dB [Fig. 5(b)]. It was confirmed that the power penalty was suppressed within 1.5 dB when a fiber-Bragg grating (0.4 nm reflection bandwidth) was used at the modulator output for removing the ±first sidebands. In this case, two modes adjacent to the locked modes induced this weak penalty, because these adjacent modes were slightly amplified due to the four-wave mixing of the locked modes in the F–P laser [4]. We believe that this tolerance against fiber dispersion is sufficient for fiber based mm-wave systems. The periodicity of 2 km was confirmed from Fig. 5(b) and agreed with equation (1) where $(\omega_{locked} - \omega_{unwanted}) \cdot (2\pi)^{-1} = 60$ GHz.

Therefore, the two-mode locked FP laser can be used as a mm-wave source in fiber-based mm-wave systems because of the carrier's low phase-noise characteristics and the tolerance against the fiber dispersion. By using the two-mode injection-locked F–P lasers, data transmission at mm-wave can be performed where an optical data signal and locked modes are wavelength-multiplexed at a central station and are optically demultiplexed at base antenna stations [1]. In addition, data modulation at the mm-wave can be carried out by external [6] or direct [7] modulation of the locked modes.

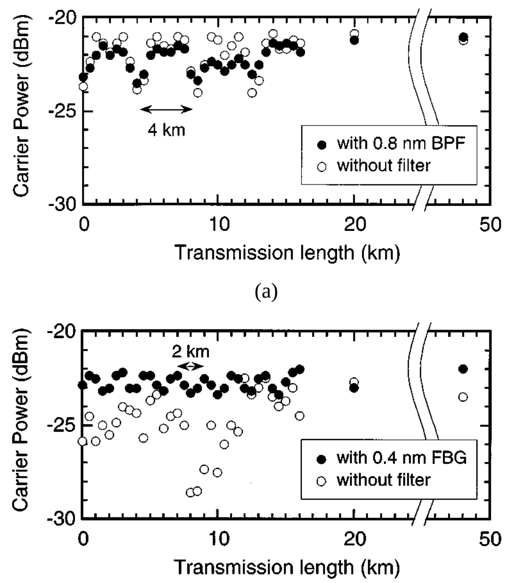

Fig. 5. (a) Relationship between the fiber length and carrier power when the reference frequency is 30 GHz. (b) Relationship between the fiber length and carrier power when the reference frequency is 15 GHz.

III. Conclusion

We have demonstrated performance of the 60 GHz carrier generation via a two-mode injection-locked F–P laser. The generated mm-wave carrier indicated low phase-noise characteristics and the immunity against the chromatic dispersion of fibers. The minimum reference frequency and the carrier's power deviation due to the dispersion were 7.5 GHz and 2.0 dB. Then, mm-wave generation based on the two-mode locked F–P laser is suitable for fiber radio systems as the mm-wave sources.

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