Optoelectronic Millimeter-Wave Synthesis Using an Optical Frequency Comb Generator, Optically Injection Locked Lasers, and a Unitraveling-Carrier Photodiode

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***Abstract*—This paper demonstrates multi-octave, milli-watt-class millimeter-wave synthesis using three key components: an optical frequency comb generator, an optical injection-locking filter, and a unitraveling-carrier photodiode. The experimental system synthesizes 10–110-GHz millimeter-wave signals with 3-dBm output at 60 GHz. Phase noise results are also presented.**

***Index Terms*—Millimeter-wave generation, optical phase-locked loops, photodiodes, semiconductor lasers.**

I. Introduction

HIGH-POWER and wide-tuning-range optoelectronic synthesis of millimeter-wave signals is of great interest for the realization of fiber-radio systems and as a measurement tool for newly developed optoelectronic and electronic devices. Applications in dense-wavelength-division multiplexing (DWDM) have led to great interest in optical frequency comb generators (OFCGs) [1] that emit multiple wavelength light with exact spectral line spacings. Using an amplified fiber loop OFCG, generation of more than 100 lines over a 1.8-THz bandwidth in the 1.55-μm band has been demonstrated [2].

If the OFCG output signal illuminates a high-speed photodiode, electrical signals at the line spacing frequency and its harmonics are generated. It is important for many applications to generate a single spectrally pure electrical signal, and this requires that only two wavelengths are derived from the OFCG output. Tunable optical filters are necessary to develop a wide-tuning-range synthesizer. Passive filters such as the array-waveguide grating and the fiber Bragg grating have been developed, but neither their tuning range is wide nor their response fast. In contrast, optical injection locking (OIL) of a laser diode is a promising technique toward the widely tunable and fast optical filter. Millimeter-wave synthesis using this technique has been reported, but the output was as low as < -47 dBm, and the maximum frequency was limited to 40 GHz by the characteristics of the photodiode [3], [4].

The millimeter-wave synthesizer can be expanded in frequency range and output power if a high-power high-speed photodiode is available. The unitraveling-carrier photodiode (UTC-PD) [5] is a strong candidate for such applications. Light is absorbed in the p-region in the UTC-PD so that only fast electrons act as carriers but generated holes remain in the p-region as majority carriers. Thus, its response is very fast, with a reported 3-dB bandwidth of 310 GHz [6], [7]. Due to the band structure, the saturation power is higher than the conventional p-i-n photodiode. A 1.5-Vpp output at a 50- Ω load has been reported, which should be equivalent to 7.5 dBm [8].

In this paper, we describe a millimeter-wave synthesizer that employs an OFCG, two OIL lasers, and a UTC-PD. Unlike the conventional OIL lasers, a superstructure-grating distributed-Bragg-reflector laser diode (SSG-DBR-LD) with wider tuning range was employed. In addition, an erbium-doped fiber amplifier (EDFA) was inserted between the OIL lasers and the UTC-PD so that not only the tuning range is wide but also the output power is high. The frequency range of the synthesizer is 10–110 GHz, and the maximum power we observed is 3 dBm. This paper also includes the details of OFCG stabilization and OIL techniques.

II. Principle and Configuration of Synthesizer

The millimeter-wave synthesizer consists of an OFCG, two OIL lasers, an EDFA, and a UTC-PD, as shown in Fig. 1[9]. The OFCG emits an optical comb with exact frequency spacing of the spectral lines equal to a reference frequency f_{RF} applied to an optical modulator in the OFCG. From more than 100 comb lines, each injection-locked laser selects only one. A distributed feedback laser diode (DFB-LD) and a SSG-DBR-LD are used as OIL lasers in Fig. 1. The two lines are combined and are then fed into an EDFA. The difference frequency is an integral multiple of the reference frequency $n \times f_{RF}$ (n: integer). The amplified laser output is input to the UTC-PD and converted to the millimeter-wave signal of a frequency of $n \times f_{RF}$. Using this system, we can achieve arbitrary frequency synthesis by changing the supplied microwave reference frequency f_{RF}, with the frequency range limited only by the UTC-PD characteristic.

Manuscript received April 21, 2003; revised September 26, 2003. This work was supported in part by the U.K. EPSRC PHOTON project.

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Digital Object Identifier 10.1109/JLT.2003.822250

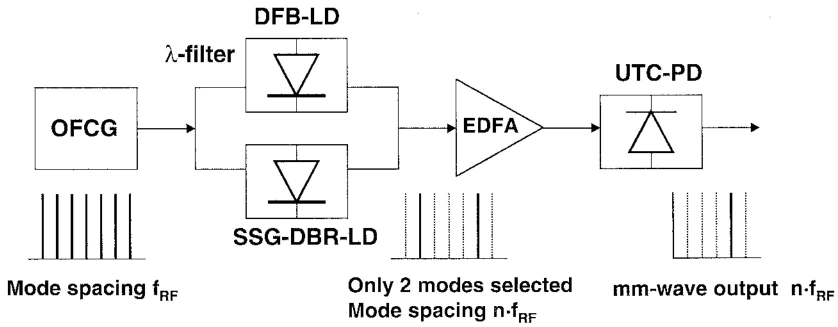


Fig. 1. Block diagram of optical millimeter-wave synthesis system.

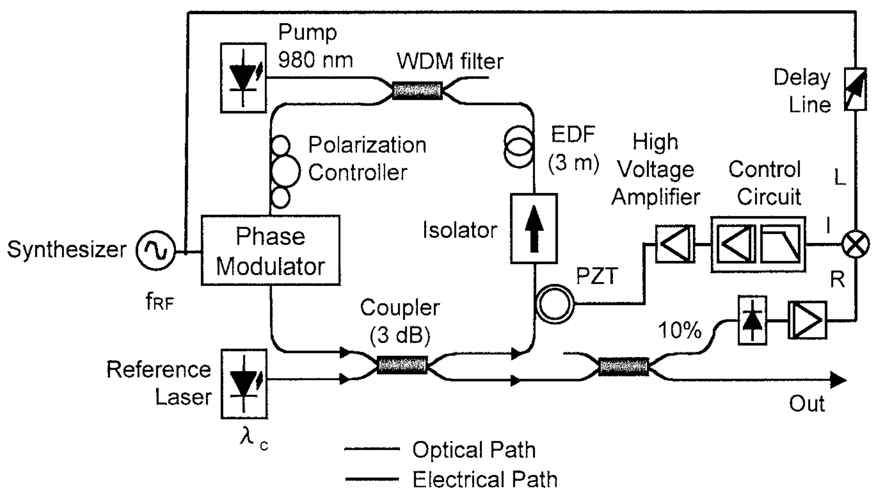


Fig. 2. Configuration of an optical frequency comb generator.

This system does not require an expensive millimeter-wave wide-band amplifier since the amplification is done optically.

The highest cutoff frequency of the UTC-PD is reported to be 310 GHz [7], and this can be regarded as sufficient for most millimeter-wave applications.

III. Experimental Arrangement

A. Optical Frequency Comb Generator

A configuration of the amplified fiber loop OFCG employed is shown in Fig. 2. A reference laser (wavelength: λc) is incident into the fiber loop in which a piezoelectric tube (PZT), an isolator, an erbium-doped fiber (EDF), a wavelength-division-multiplexing (WDM) filter, a polarization controller, and an optical phase modulator are connected. The single-mode reference laser input is phase-modulated at the f_{RF} frequency spacing to produce multiple spectral lines. The optical loss in the loop is compensated, using the 980-nm pump laser and the EDF. Further spectral lines are produced by phase modulation of the light with each recirculation through the loop. The function of the PZT is to stabilize the loop length, since the total optical length is easily changed due to the room temperature instability. This technique is described subsequently in detail.

In the experiment, we used a tunable laser as a reference laser with a wavelength of 1528–1560 nm and a microwave oscillator with a reference frequency f_{RF} of 10 GHz. Frequencies of 15 and 17.5 GHz were used in some experiments. A typical comb output spectrum is shown in Fig. 3. As the pump power increases, the comb range is expanded more widely. In the $>$ 1.8 THz range, we can see more than 100 lines with exact spacing of 17.5 GHz contained within a 40-dB power envelope. The large emitted span of comb generator makes it possible to

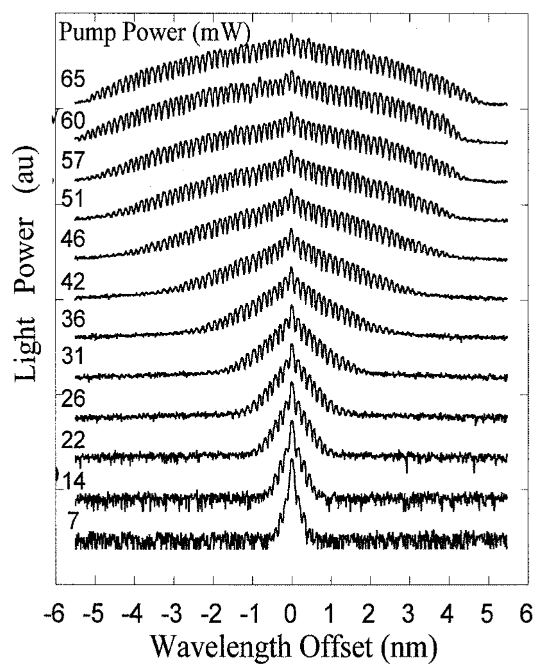


Fig. 3. Output spectrum from an OFCG.

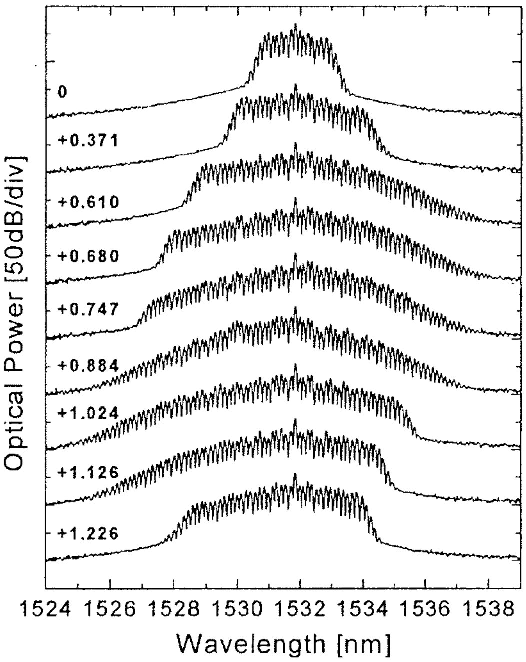
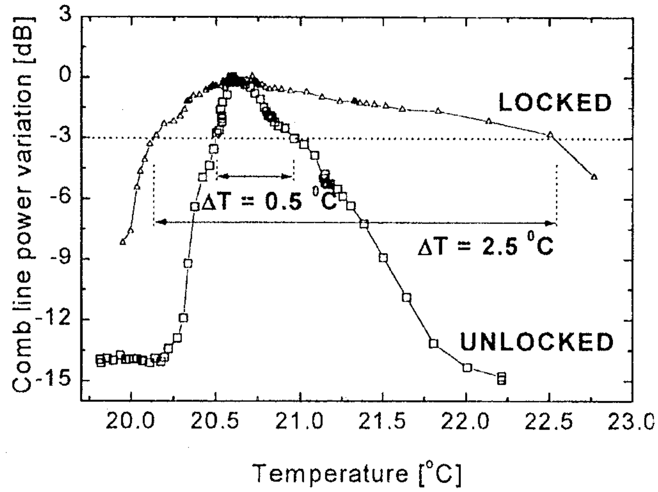
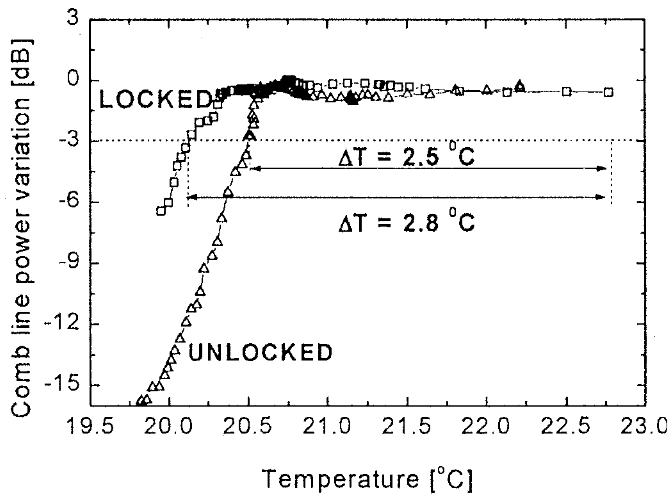


Fig. 4. Comb spectrum without the temperature compensation.



(a)



(b)

Fig. 5. Comb line power variation dependence on the temperature. The wavelength difference between the comb line and reference laser is 5.7 nm for (a) and 2.4 nm for (b).

select comb lines of sufficient spacing to generate signals at up to 1.8 THz, although the highest frequency generated in our experiment was 110 GHz due to measurement limitations. The wider comb is helpful in the experiment since each comb line intensity is approximately the same and the injection conditions are relaxed.

The entire length of the loop is about 20 m; hence, the fiber length instability was troublesome in our experiment. If the fiber length is detuned, the comb spectra is not fully expanded to the previous value of 1.8 THz. Fig. 4 shows some example spectra with a parameter of room temperature change over a 1.3-K range. Note that the widest comb generation occurs over quite a limited temperature range. The temperature has to be kept within $+/-0.1$ K to maintain optimum performance.

To overcome this problem, we stabilized the fiber length by using a PZT in the loop. The driving voltage of the PZT is generated by the comparison of the reference and the synthesized RF signal phase, using the circuit of Fig. 2. Fig. 5(a) and (b) shows the improvement obtained by adding this control loop. For a reference wavelength of 1531.0 nm, the variation in the power of the generated comb line spaced 5.7 nm from the reference wavelength at 1536.7 nm with temperature is shown in Fig. 5(a). When the feedback loop is locked, 2.5° are permissible for a -3 dB power variation. When the loop is unlocked, only 0.5° are permissible for the same power variation. The result in Fig. 5(b) was measured for a comb wavelength that is closer to the reference wavelength. The wavelength difference between the measured comb and reference is 2.4 nm. For the locked and unlocked conditions, the permissible temperature ranges are > 2.8 and $> 2.5°$. From these results, it is shown that the PZT locking method is effective in compensating for fiber length change due to the temperature. Further, it is shown that comb lines closer to the reference wavelength are less sensitive to temperature than those at the extremities of the generated spectrum.

B. Superstructure-Grating Distributed-Bragg-Reflector Laser Locking

A conventional laser can be used as an optical-injection-locked filter by changing its temperature and current; however, its locking range is limited. For wide-range heterodyne signal generation, we can use a conventional laser for one injection-locking filter, but we have to use a widely tunable laser such as a SSG-DBR-LD [10]. This section describes the tuning performance of the SSG-DBR-LD. The laser has a front and a rear gain section and a phase-matching section. This structure enables electronic wavelength tuning.

Prior to millimeter-wave synthesis experiments, we measured wavelength tuning range and side-mode suppression ratio. Fig. 6 shows a map of lasing wavelength with two axes of the front- and rear-section currents. The currents were changed form 0 to 20 mA and, then, the lasing wavelength was observed to tune over from 1528 to 1565 nm. A tunability of at least 37 nm was experimentally confirmed with a minimum power of 0.2 mW. Fig. 7 shows a side-mode suppression ratio map with the same

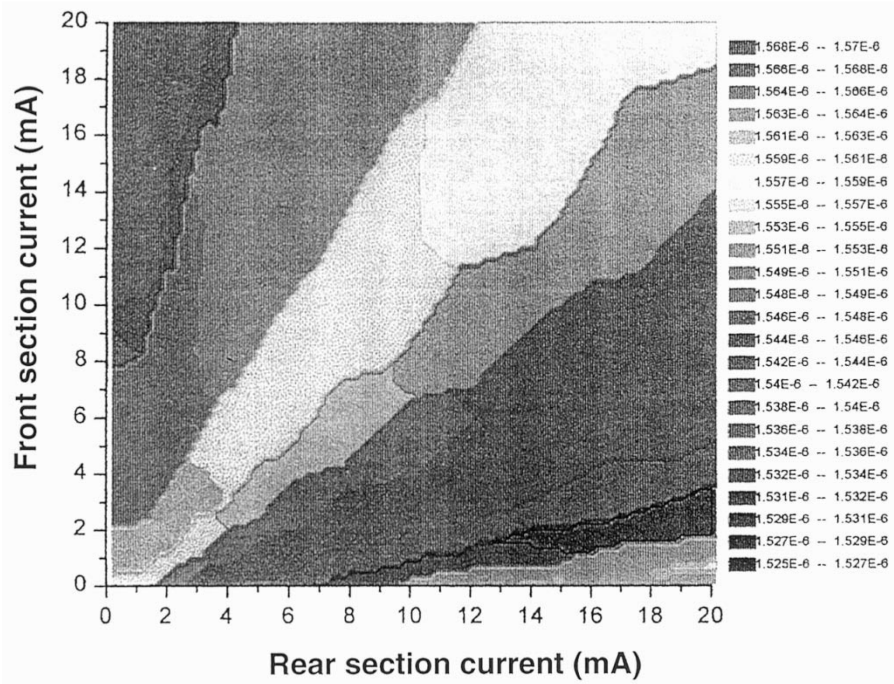


Fig. 6. Map of lasing wavelength with front- and rear-section currents.

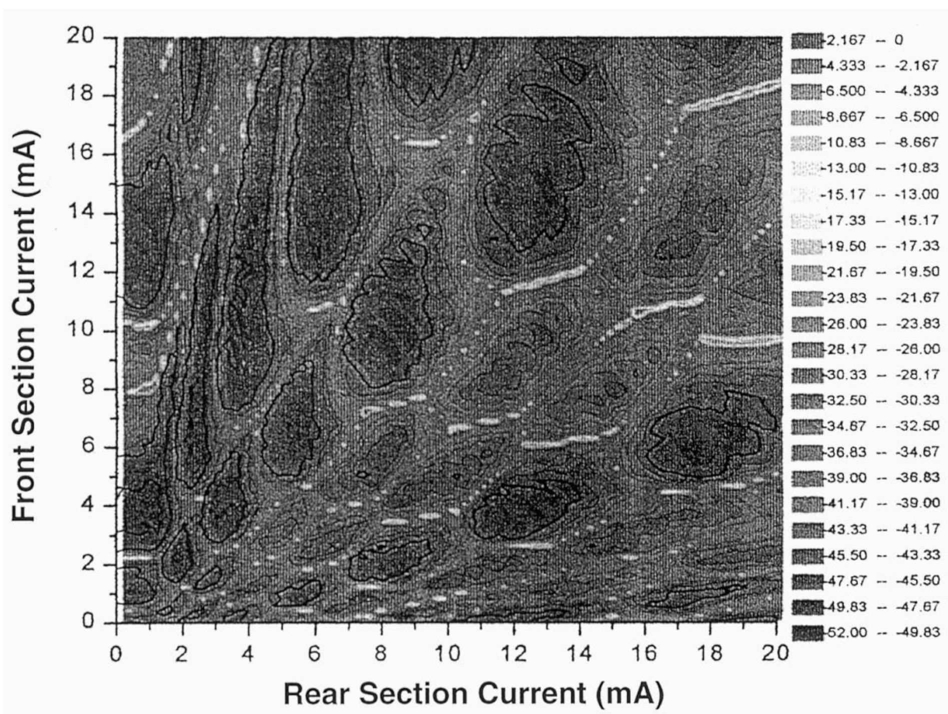


Fig. 7. Side-mode suppression ratio map with the same axes as Fig. 6.

axes as Fig. 6. Except for some mode boundaries, the worst ratio observed is -32, which is sufficient for the millimeter-wave synthesis application.

Next, we show the optical-injection-locking characteristics. An optical-injection-locking laser is a convenient wavelength filter with an optical gain, although it works within limited condition, such as injected power and frequency detuning between the laser's free-running frequency and the injected one. Fig. 8 is a map of locking characteristic variation with the power injection ratio and frequency detuning. Lasing behaviors are divided into three classes. At the zero detuning and near the zero detuning and moderate ratio (V- shaped), the injected laser is stably locked. As the injection ratio becomes higher than the V shape, the laser is locked but is not stable. Beneath the V shape, the injection power is too small to lock the laser to the injected frequency. As a result, we can use the optical-injection-locked laser as a filter within the V-shaped parameter space.

A lot of comb lines are incident on the OIL laser simultaneously, and all the lines other than the wanted one are unwanted injection. Note that these unwanted injection lines could make

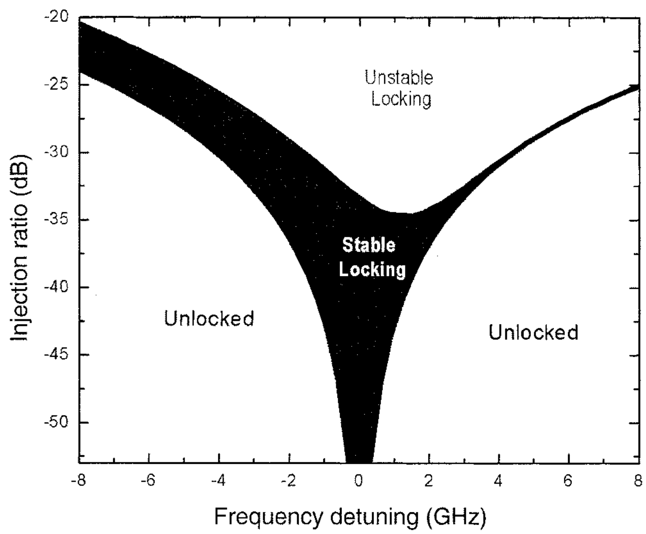


Fig. 8. Map of locking conditions with power injection ratio and frequency detuning.

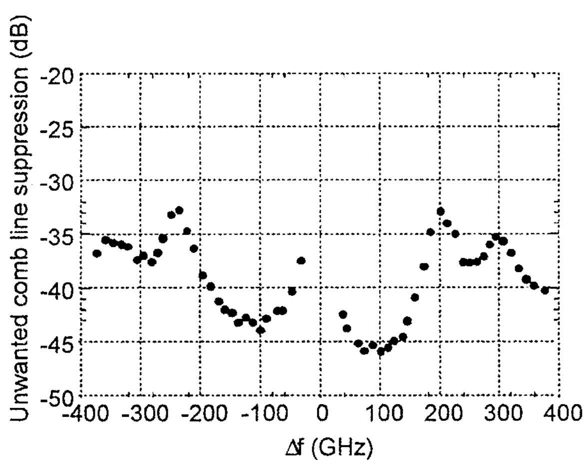


Fig. 9. Unwanted comb line suppression dependence on detuning.

the laser unstable and/or make the laser emit side modes. Fig. 9 shows the unwanted comb line suppression dependence on the detuning. The worst ratio was observed as −32.5 dB in our measurement range, −400 to 400 GHz. The injection ratio was −30 dB. Sufficient suppression was obtained experimentally.

The wide tuning range of the SSG-DBR-LD laser would allow the selection of generated frequencies of $>$ 10 THz range, given a comb source of sufficiently wide span. However, where only signals in millimeter-wave range are to be generated and the time delays inherent in temperature tuning are acceptable, a temperature and current tuned DFB-LD could be substituted for the SSG-DBR-LD.

C. Unitraveling-Carrier Photodiode

The structure and operation of the UTC-PD has been reported in detail elsewhere [5]–[8]; hence, this is a short review. As shown in Fig. 10, the UTC-PD is a hetero-junction photodiode that has a narrower band gap absorptive p-region. When a photon is absorbed in the p-region, an electron-hole pair is generated. The electron moves into the n-layer with high velocity.

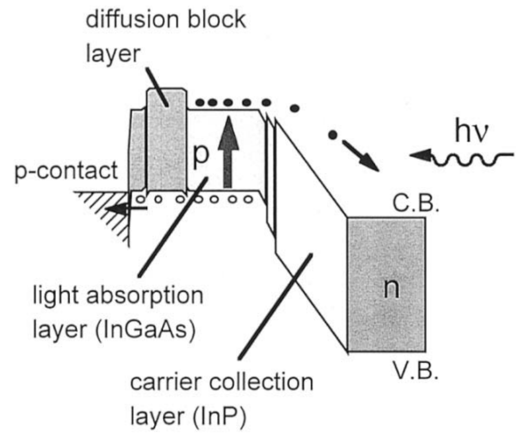


Fig. 10. Band diagram of a UTC-PD. C.B.: Conduction band. V.B.: Valence band.

The hole is a slow carrier; however, it remains in the p-region as a majority carrier. As a result, the response is determined only by the electron velocity. In addition, saturation power is reported to be 13 dBm at 100 GHz, which is much higher than a conventional photodiode. Radio access points have been developed that do not require expensive millimeter-wave amplifiers through the use of UTC-PDs by fully utilizing these characteristics [11], [12].

The UTC-PD employed has an edge-coupling interface, giving a responsivity of 0.4 A/W and a 3-dB bandwidth of $>$ 60 GHz at the −4-V bias voltage. The optical coupling was through a lensed fiber with an excess loss of 3 dB. We used ground–signal–ground co-planar probes to collect millimeter-wave power generated from the UTC-PD chip. The losses of the probes were 0.83 and 1.3 dB at 60 and 110 GHz, respectively.

IV. Experimental Results

The complete experimental system is shown in Fig. 11. The OFCG, wavelength filter, and optoelectronic converter are connected in series. The synthesized millimeter-wave signal is observed using a millimeter-wave spectrum analyzer. Agilent mixers, 11 974U and 11 970W, were added to measure 60 and 75–110 GHz outputs, respectively. The optical comb is observed by an optical spectrum analyzer (OSA) and by a Fabry–Pérot analyzer (FP) when needed.

The generated comb spectrum is shown in Fig. 12. The center wavelength of the comb is 1557.2 nm, and the line spacing is 10 GHz. The two lines selected by the injected lasers are shown as well. The comb spectrum is wide enough, and the unwanted side modes near the selected lines are suppressed. This laser light was amplified by the EDFA and was converted into a millimeter-wave signal by the UTC-PD. The detected spectrum is shown in Fig. 13 for an input power into the UTC-PD of 17 dBm, an average photocurrent of 10 mA, and a bias voltage of −4 V. Next, we measured the dependence of the UTC-PD millimeter-wave output power on optical input power, as shown in Fig. 14. The results are linear with a slope of 2 on the log plots, showing that the output power is proportional to the square of the optical input power before saturation since the photocurrent

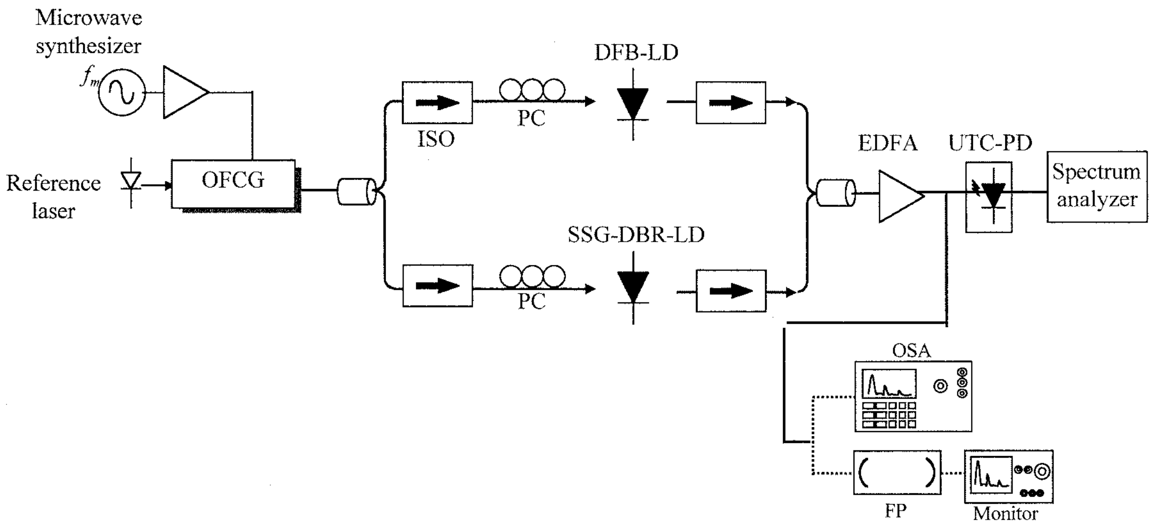


Fig. 11. Complete experimental system. PC: Polarization controller.

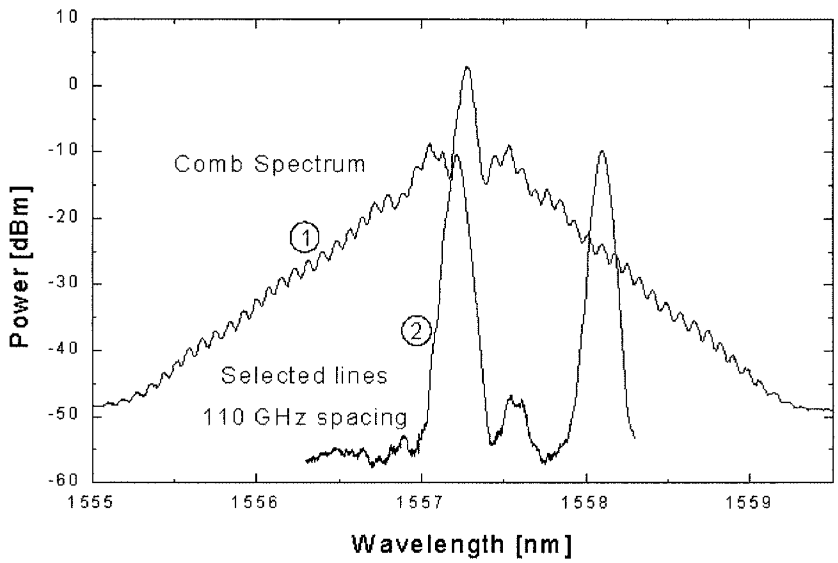


Fig. 12. Optical spectra from the OFCG and the optical injected lasers.

is proportional to the input power. The dependence is linear up to 15-dBm input for all the frequencies. Only at 80 GHz was slight saturation observed between 16- and 17-dBm input. The maximum power obtained was 3 dBm at 60 GHz, when the input power was 19 dBm, the limit of our EDFA. At the highest frequency of 110 GHz that is also our measurement limit, an output power of −9.8 dBm was observed for 17.8 dBm optical input to the UTC-PD. We could expect higher power to be obtainable with a higher power EDFA since the UTC-PD does not show saturation for frequencies lower than 60 GHz.

Fig. 15 shows frequency responses for small (1.8-dBm input) and large (17-dBm input) optical signals. The small-signal 3-dB bandwidth is estimated to be 85 GHz from interpolation and its flatness $+/-1.4$ dB. The experimental bandwidth meets with the response specification of the employed UTC-PD of $>$ 60 GHz. The large signal bandwidth is 70 GHz, and its flatness is $+/-1.3$ dB. As a result, our system functions as a 10–110-GHz synthesizer with milliwatt-level output.

V. Phase-Noise: Discussion

Phase noise is an important characteristic for any synthesizer. Fig. 16 shows single-sideband (SSB) phase-noise spectra of the synthesized 110-GHz signal and that due to the originating reference RF signal. In all ranges of frequency offset, the phase noise of the generated signal is 15–35 dB higher than that due to the reference. We made the same measurement at 10-kHz offset for the all frequency ranges, 10–110 GHz, as shown in Fig. 17. The phase noise is very flat with an average of -79 dBc/Hz and a variation of $+/-0.8$ dBc/Hz for frequencies of $<$ 80 GHz. Then, the phase noise increases as the frequency becomes higher.

In addition to the experimental results, we have plotted two lines in Fig. 17. One line is the theoretical limit when optical injection locking is used [13], [14]. The parameters for this calculation are a linewidth of the reference laser of 1 MHz and a path-length error between the two injection-locked lasers of 5 cm.

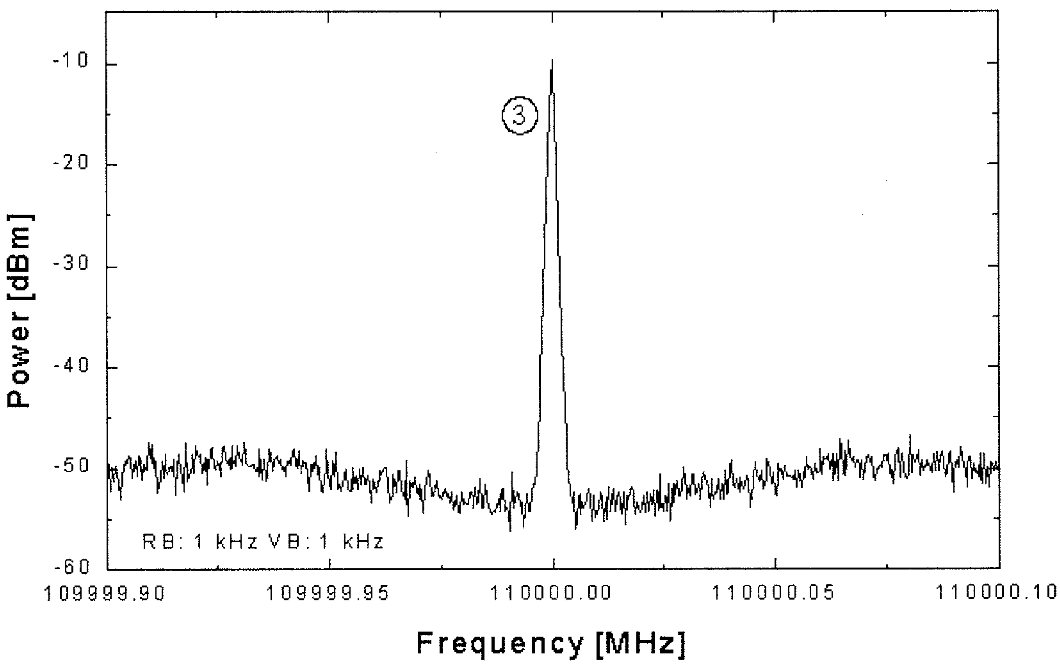


Fig. 13. Millimeter-wave spectrum generated by the UTC-PD. Center frequency: 110 GHz.

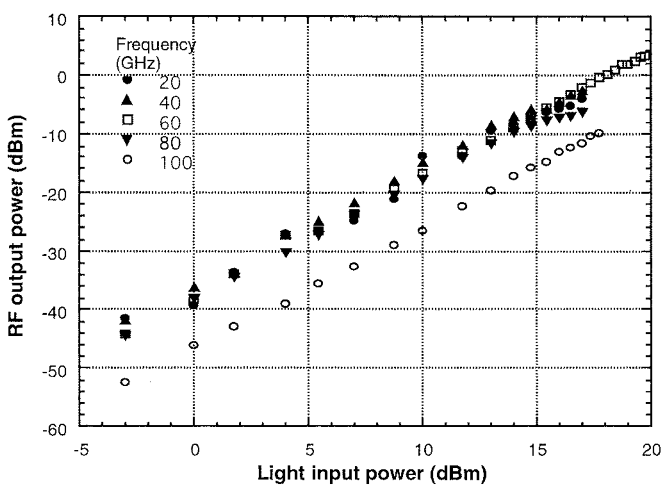


Fig. 14. Millimeter-wave output power as a function of optical input power.

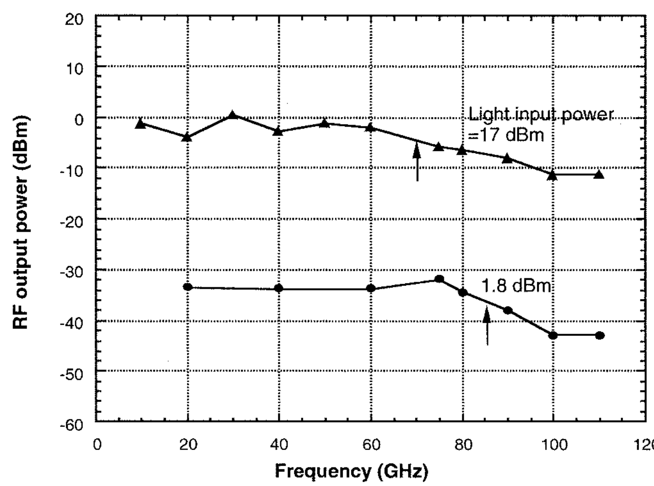


Fig. 15. Frequency response of the UTC-PD measured by synthesis system.

The other comes from RF reference noise that is extrapolated from the experimental value at 10 GHz with a 20-dB/decade slope. The experimental result shows good agreement qualitatively with two lines although they differ by approximately 10 dB. As suggested by two lines, the SSB phase noise is constant for frequencies $<$ 80 GHz, governed by the OIL theoretical limit, and it increases with a 20-dB/decade slope at frequencies $>$ 80 GHz due to the RF reference noise.

Let us consider why the experimental and theoretical curves differ by 10 dB. The major source of the excess phase noise observed is intensity-noise-to-phase-noise conversion in the optical-injection-phase-locked loop, arising from intensity fluctuations in the comb lines [1], [14]. In our case, the theoretical OIL phase noise is calculated under the assumption that every comb line power is of constant power; however, in practice, the fluctuations arise from environmentally induced loop-length variations and supermode competition within the comb generator, even with the PZT feedback loop. It should be noted that the feedback is performed only for low-frequency fluctuations ($<$ 1 kHz) because it requires a high-voltage driver that is usually slow. To compensate the small-signal high-frequency fluctuation occurring just before the OIL, a phase modulator for optical loop-length tracking should be added. Moreover, comb generator techniques using shorter loop lengths would be expected to offer smaller penalties.

VI. Summary

We have shown that the combination of the OFCG, OIL, and UTC-PD produces a high-power multi-octave tunable millimeter-wave signal. The maximum power obtained was 3 dBm at a carrier frequency of 60 GHz, limited by the EDFA

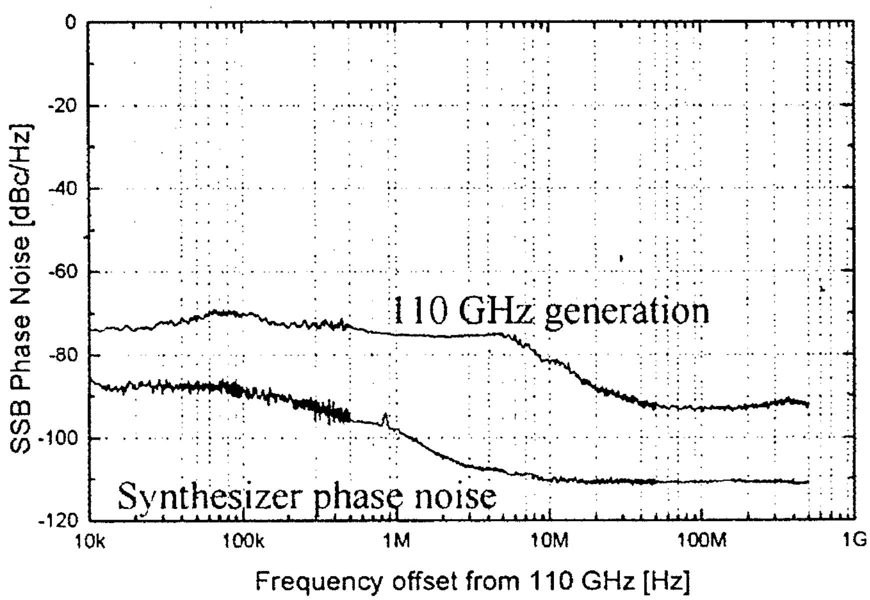


Fig. 16. Phase-noise spectra from the OFCG and due to the RF reference employed.

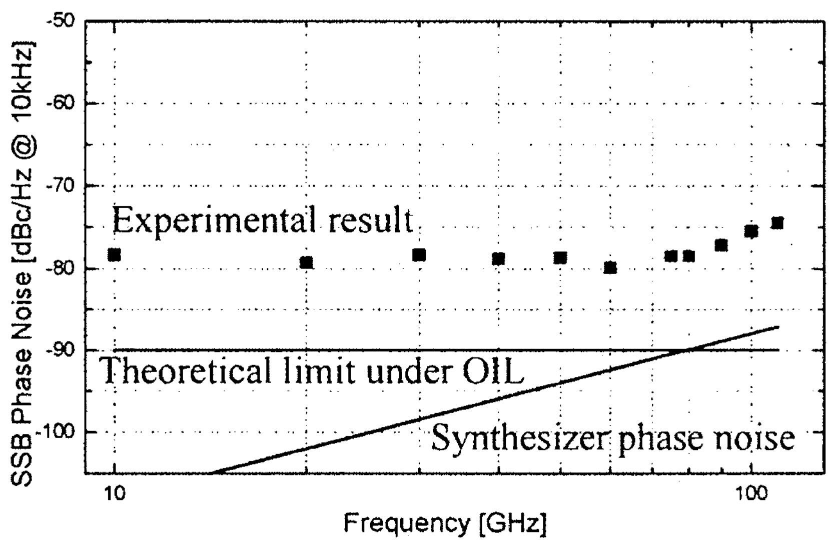


Fig. 17. Phase-noise plots versus the generated frequency.

output power. We measured the phase noise of the generated millimeter-wave signals and compared the results with theoretical limits. It was suggested that the experimental values of phase noise are governed by the amplitude-to phase noise conversion in the locked lasers and that this can be further reduced by fast fiber-length contol.

This approach can play an important role in millimeter-wave signal generation for emerging fiber-fed wireless applications since the upper frequency limit is mainly set by the photodiode bandwidth.

ACKNOWLEDGMENT

The authors would like to thank Dr. H. Ito and Dr. T. Ishibashif for their fruitful suggestions.

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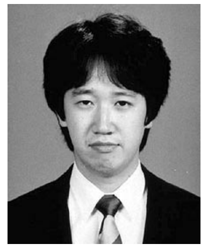
C. F. C. Silva (S'03), photograph and biography not available at the time of publication.



Y. Muramoto was born in Tokushima, Japan, on March 15, 1967. He received the B.E. and M.E. degrees from Osaka Prefecture University, Osaka, Japan in 1990 and 1992, respectively.

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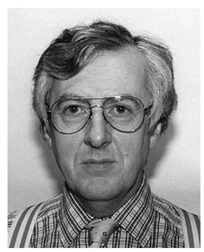

Alwyn J. Seeds (F'97) received the Ph.D. and D.Sc. degrees from the University of London, London, U.K.

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Prof. Seeds is Chairman of the Institution of Electrical Engineers (IEE) Photonics Professional Network and a Fellow of the Royal Academy of Engineering. He has served on the program committees for many international conferences.