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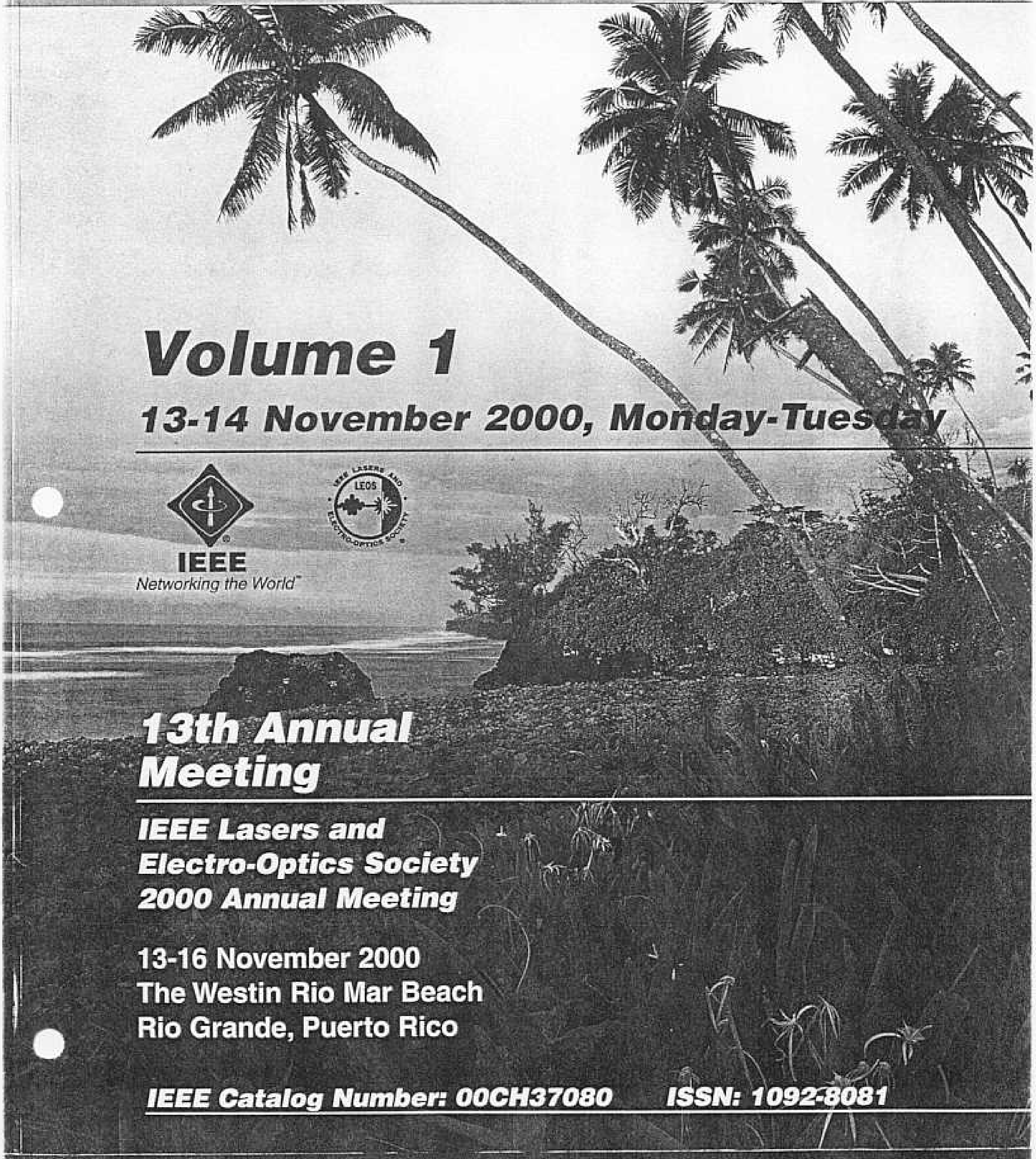

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Optical Millimeter-Wave Generation by Locking of Four-Wave-Mixing Conjugate Modes in DFB Lasers

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The optical generation of millimeter-wave (MMW) signals has been attracting much interest for many applications, such as broadband wireless communications and optical beam forming, because of its flexibility in generating high-frequency signals. In particular, the side-band injection-locking is a promising technique since it has a simple configuration and is able to produce pure and stable MMW signals [1,2]. Braun *et al.* used two slave lasers (SLs) to select the target modes among several side-bands generated in the rf-modulated master laser (ML), and have two selected modes beat each other in the photodiode (PD) to produce 60GHz [1]. Nöël *et al.* demonstrated the generation of 60GHz by injecting continuous wave (cw) ML light into the rf-modulated SL, and beating ML with a selected SL side-band [2]. In these techniques, however, the maximum achievable MMW frequency is limited by the rf-modulation performance of ML or SL. In this paper, we demonstrate a new technique, which does not have such limitation.

Our scheme utilizes the locking of Four-Wave-Mixing (FWM) conjugates produced in a DFB laser (SL) by the light injection from another DFB laser (ML). Fig. 1 shows the experimental set-up used in our study. When the ML lasing wavelength is set lower than the SL lasing wavelength outside the locking region, FWM occurs [3]. The ML and SL peaks and the FWM conjugates can be observed as shown in Fig. 2. The frequency separation between FWM conjugates are equal to the frequency difference between ML and SL, which is set at about 14 GHz in our experiment. By selecting two conjugate modes, we can produce the beat frequency that is a harmonic of 14 GHz. This beat signal, however, is not stable as shown in Fig. 3. In our experiment, the beat signal frequency was observed to fluctuate by several hundred MHz. In order for this beat signal to be of any use, the FWM conjugates should be locked to each other.

In order to achieve this, we simultaneously rf-modulated (3GHz) both ML and SL so that side-bands are produced both in ML and SL. If any of the SL side-bands are injection-locked by the ML side-bands, then SL and the entire FWM conjugate modes produced by light injection from ML to SL are locked. Fig. 4 shows the RF spectrum of the beat signal. There are clear signals at the multiples of 3GHz. It should be noted that these are not simply higher order harmonics of 3 GHz, the modulation frequency, as there are signal intensity increase at the intervals of about 14 GHz, the frequency for FWM conjugate mode separation. Consequently, beat signals at much higher frequencies can be observed. In our case, the highest beat signal observed was 42 GHz, which is almost limited by the PD used in the experiment. Fig. 5 shows the measured rf-spectrum and phase noise of the beat signals at 30 GHz. It is very stable and its phase noise is −81 dBc/Hz at 100kHz offset.

In summary, we demonstrated that the side-band injection locking between FWM conjugate modes in a DFB laser under the external laser light injection can produce stable MMW signals. Since the produced MMW signal frequency is determined by the conjugate mode separation, which can be very large, we believe that this is quite useful for producing very high-frequency optical MMW signals.

References

[1] R. P. Braun et al., MTT-46(4), 1998, 320-329.
[2] L. Noël et al., MTT-45(8), 1997, 1416-1423.
[3] J. Troger et al., JQE-35(1), 1999, 32-38.

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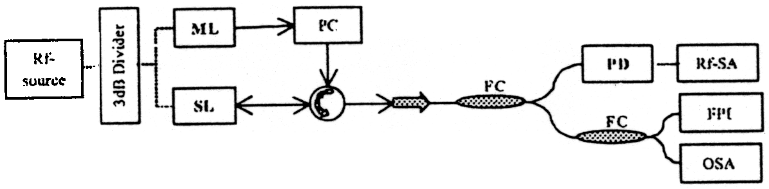

Fig. 1 Experimental setup. PC is polarization controller, FC fiber coupler, Rf-SA rf-spectrum analyzer, FPI Fabry-Perot interferometer, and OSA optical spectrum analyzer. The arrow indicates the optical isolator.

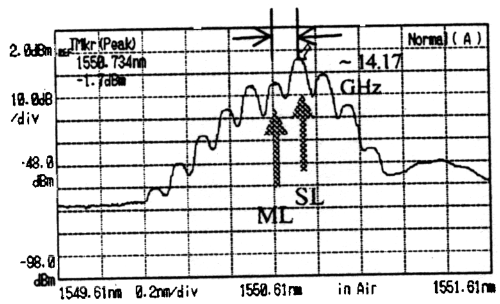

Fig. 2 Optical Spectrum of cw SL under cw ML light injection. The arrows indicate the wavelengths of ML and SL. The other peaks are the FWM conjugates.

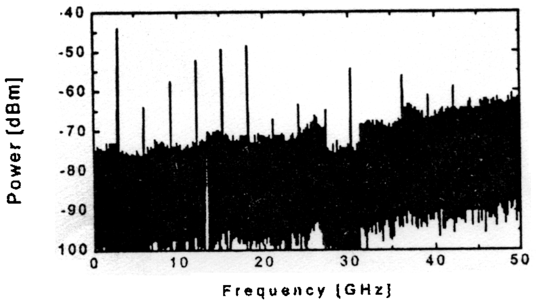

Fig. 4 Photo-detected rf-spectrum of rf-modulated SL under rf-modulated ML light injection.

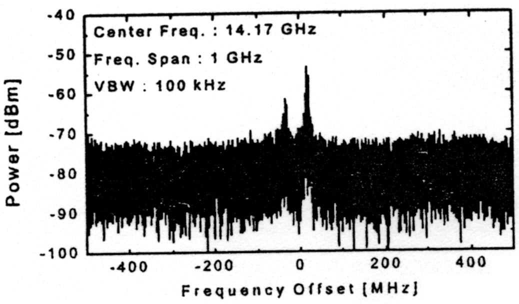

Fig. 3 Photo-detected rf-spectrum of Fig. 2.

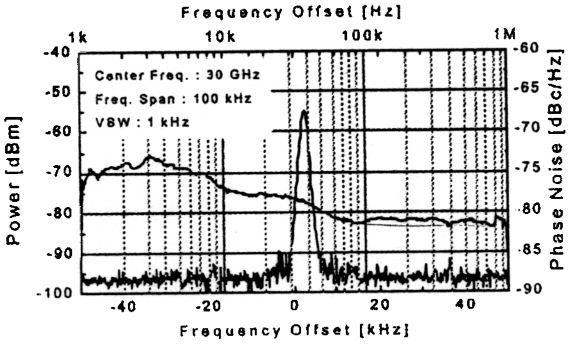

Fig. 5 Rf-spectrum and phase noise of 30 GHz in Fig. 4