# Locking Range of a Hybrid Mode-Locked Monolithic DBR Semiconductor Laser at Millimeter-Wave Frequencies

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*Abstract*— **We present the first investigation of the detuning characteristics at 33 GHz of a hybrid mode-locked monolithic distributed Bragg reflector semiconductor laser. Hybrid mode-locking is achieved by applying a radio-frequency (rf) signal, at a frequency corresponding to the fundamental laser repetition frequency, to the saturable absorber of the passively mode-locked laser. Measurements show a 3-dB locking range greater than 40 MHz with an applied external rf signal power of 0 dBm. At this power level, the laser beat signal exhibited phase-noise less than −78 dBc/Hz and −93 dBc/Hz at 10 kHz and 5 MHz offsets, respectively.**

## I. Introduction

There is presently much interest in the generation and transmission of microwave and millimeter-wave (mm-wave) signals using optical techniques. Applications of microwave and millimeter-wave optical fiber links include beam-forming networks in optical phased array radar systems [1], optical fiber feeds and distribution for wireless communications [2], and distribution of signals for satellite antennas [3]. The transmission of millimeter-wave signals on optical carriers for telecommunication applications is of particular interest as a result of the allocation of millimeter-wave frequencies for wireless communication systems to overcome crowding in the lower frequency spectrum [4]. Mobile and personal radio systems at millimeter-wave transmission frequencies also offer the advantages of smaller equipment and antennas. Consequently the inherent advantages of optical fiber over coax and waveguide as a transmission medium have led to the consideration of the optical generation and distribution of mm-wave signals.

Semiconductor lasers have the potential to generate very low phase-noise millimeter-wave frequencies and are a compact source of such signals [5]–[9]. We have recently demonstrated the generation of ultra-stable mm-wave signals using a monolithic passively mode-locked distributed Bragg reflector (DBR) semiconductor laser [10]. In order to reduce the phase-noise of the detected beat signal from the laser, an external rf signal at a frequency corresponding to the fundamental laser repetition frequency was applied to the saturable absorber (SA) of the device. A beat signal at 33 GHz with phase-noise less than −70 dBc/Hz at 5 kHz offset was demonstrated with an applied rf power from the synthesizer of less than 0 dBm. Since the monolithic DBR laser also emitted an optical power greater than 2 mW (after coupling into a standard single-mode fiber), a post-detection rf power greater than −45 dBm was achieved.

For the application of the hybrid mode-locked monolithic DBR laser as a source of mm-wave signals in optical fiber microcellular and picocellular communication systems, the frequency tuning capability of the detected beat signal is an important characteristic. In this paper, we continue our investigation of the hybrid mode-locked DBR laser and present detailed measurements of the detuning characteristics of this technique. This is the first investigation of the detuning behavior at millimeter-wave frequencies of a hybrid mode-locked monolithic DBR semiconductor laser. Phase-noise measurements at offset frequencies close-in and far from the carrier are presented and the locking range as a function of the applied rf power has been determined. A maximum locking range greater than 40 MHz is achieved with an applied signal power of 0 dBm.

## II. Experiment

The monolithic passively mode-locked DBR laser is a four-section device consisting of DBR, phase control, gain, and saturable absorber regions [11]. The saturable absorber and the gain sections are composed of the same graded-index separate confinement heterostructure multiquantumwell material with three 40-Å-thick InGaAs wells separated by InGaAsP barriers of 130 Å thickness. The phase control and the DBR sections of the laser consist of a quaternary bulk semiconductor material which has 1.3-$\mu$m band-gap wavelength. The total length of the laser chip was 1.28 mm giving a fundamental repetition frequency of approximately 33 GHz.

To achieve hybrid mode-locking and reduce the phase-noise of the detected beat signal, an external rf signal at 33 GHz is applied to the SA of the laser. Fig. 1 shows the experimental setup of the hybrid mode-locking technique. No reverse bias was applied to the SA in these experiments and no impedance matching between the laser and the synthesizer was attempted. The current applied to the gain section of the laser was 152 mA while the DBR and phase control sections were left with open-circuit terminations. The laser output was coupled into

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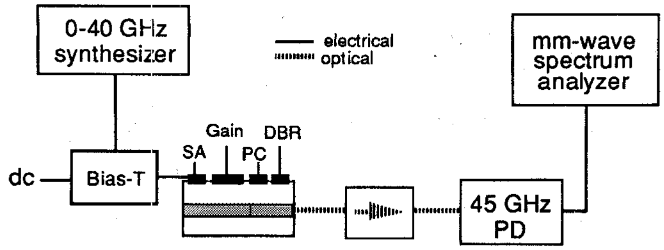


Fig. 1. Experimental setup of hybrid mode-locking of monolithic DBR laser.

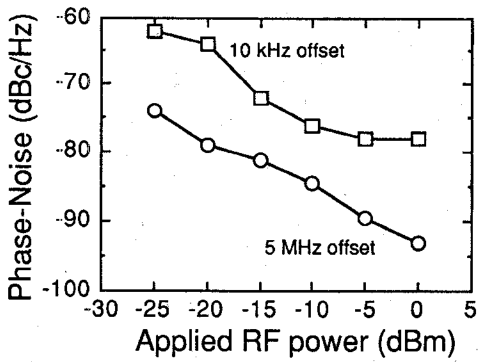


Fig. 2. Measured phase-noise of hybrid mode-locked laser versus applied rf power to the SA.

a single-mode fiber through an optical isolator with more than 40 dB isolation to prevent any reflections back into the laser cavity affecting the phase-noise measurements. The rf spectrum of the beat signal was measured using a 40-GHz spectrum analyzer in conjunction with a 45-GHz photodiode (PD).

## III. Results

Fig. 2 shows the measured phase-noise of the detected beat signal at 10 kHz and 5 MHz offset frequencies from the carrier at 33 GHz as the signal power applied to the saturable absorber is varied from −25–0 dBm (measured at the K-connector to the SA). The applied rf signal frequency was equal to the fundamental repetition frequency of the laser. The expected reduction in phase-noise with increasing rf power to the SA is clearly evident. No amplification of the external signal at 33 GHz was necessary in our experiments to achieve a beat signal phase-noise of −78 and −93 dBc/Hz at 10 kHz and 5 MHz offsets, respectively, with 0 dBm applied rf power. The phase-noise of the detected signals is also limited by the phase-noise of the synthesizer at 33 GHz (−90 and −95 dBc/Hz at 10 kHz and 5 MHz offsets, respectively).

To investigate the detuning characteristics of the hybrid mode-locked laser, the applied rf signal frequency, $f_{\text{ext}}$ was detuned from the laser cavity resonance, $f_{\text{rep}}$. It was observed that as $f_{\text{ext}}$ approaches $f_{rep}$, the laser beat frequency is pulled to the applied signal and increases in power. This effect is similar to that observed in [9]. The measured change in rf power of the detected laser beat signal as the external rf signal frequency is varied, is shown in Fig. 3 for several values of applied power. In this graph, 0 detuning corresponds to $f_{\text{ext}} = f_{\text{rep}}$ and positive detuning occurs when $f_{\text{ext}} > f_{\text{rep}}$. In order to enable the 3 dB locking range to be easily determined, the $y$-axis in Fig. 3 presents the difference between the peak signal power when $f_{\text{ext}} = f_{\text{rep}}$ and the signal power at nonzero detunings. The results show how the locking range increases when the rf power applied to the SA of the laser is increased. The measured locking range is presented in Fig. 4 and a value greater than 40 MHz at 0 dBm applied power was achieved. Note that this locking range was achieved without requiring costly mm-wave amplifiers. Significantly larger locking ranges could be achieved with narrowband mm-wave amplifiers providing rf powers greater than 0 dBm.

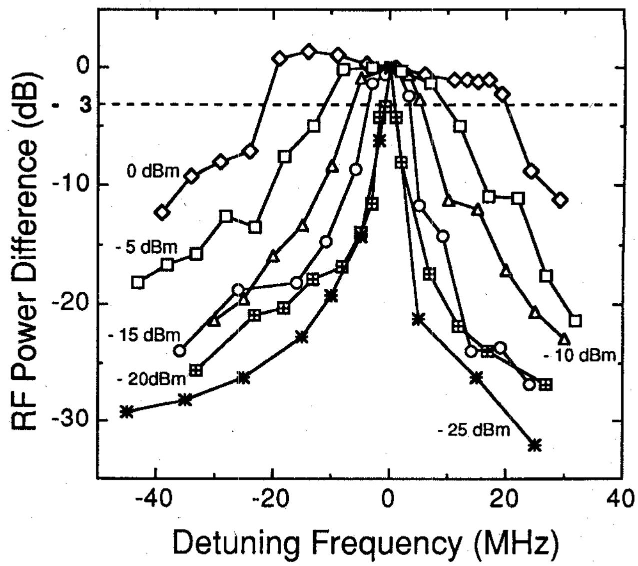


Fig. 3. Measured detuning characteristics of hybrid mode-locked laser at several applied rf power levels.

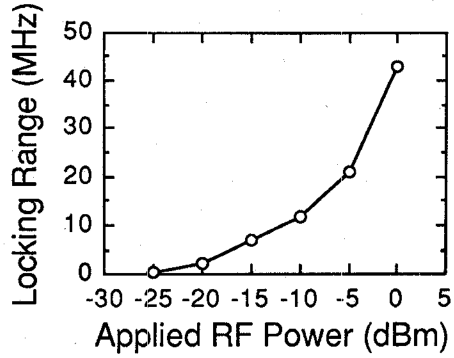


Fig. 4. Measured 3-dB locking range versus applied rf power.

It should be noted that an estimate of the locking range can also be obtained by measuring the locking bandwidth of the mode-locked laser, which is usually defined as the frequency range over which the external signal applied to the laser can be varied to give the same signal phase-noise as that obtained at zero detuning [10]. In our measurements we observed that for the range of frequencies which form our definition of 3 dB locking range (at a particular applied rf power), the phase-noise of the locked laser output signal was very close to the value of phase-noise at zero detuning.

Fig. 3 also shows that the change in beat signal power as $f_{ext}$ is varied is not symmetrical about the zero detuning point. We are presently carrying out a theoretical investigation into the locking characteristics of the hybrid mode-locked DBR laser in order to explain this behavior.

## IV. Conclusion

We have presented the first detailed measurements of the locking characteristics of a monolithic distributed Bragg reflector laser with hybrid mode-locking at 33 GHz. With an applied rf signal power of 0 dBm to the saturable absorber of the laser, the measured 3 dB locking range was greater than 40 MHz. The phase-noise of the beat signal at this applied power level was as low as −78 and −93 dBc/Hz at 10 kHz and 5 MHz offset frequencies, respectively. The relatively low signal power needed for hybrid mode-locking of this laser and the integrated laser package indicate the excellent potential of this laser in practical applications of millimeter-wave modulated optical signals.

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