Fiber-Optic Transport *and* RF Phase Control of Narrowband Millimeter-Wave Signals Using Multicontact Monolithic Semiconductor Lasers

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ABSTRACT

We demonstrate simultaneous fiber-optic transport *and* continuous RF phase control of narrowband millimeter-wave signals using a three-section monolithic Distributed Bragg Reflector (DBR) laser. By injection-locking the laser at the cavity round-trip resonant frequency of 45 GHz, 360° of continuous, linear RF phase control of the input mm-wave signal is achieved by simply varying the bias current into the laser.

INTRODUCTION

Optical transmitters capable of efficiently transporting narrowband millimeter-wave (mm-wave) signals to/from fiber-fed antenna sites in applications such as narrowband mm-wave phased-array systems and indoor mm-wave wireless picocellular networks are of considerable interest. The ability to simultaneously transport and continuously control the phase of mm-wave signals within the same optical transmitter eliminates the need for bulky waveguide phase shifters or true-time-delay fiber-optic networks, greatly simplifying the design and implementation of these systems. Recently, it was shown that the technique of resonant modulation of a conventional, low-frequency (direct modulation bandwidth <5 GHz) monolithic Fabry-Perot laser at the cavity round-trip frequency can be used to build simple, efficient, low-cost narrowband optical transmitters at subcarrier frequencies up to 100 GHz [1,2]. In this paper, we utilize the nonlinear properties of resonant modulation to obtain fiber-optic transport over 2.2 km *and* simultaneous continuous RF phase control of the input mm-wave signal. By injection-locking a three-section DBR laser at an intermodal frequency of 45 GHz, continuous phase control is achieved over 360° by simply varying the bias current into the laser. Measurements of the locking bandwidth and carrier-to-noise ratio (CNR) at 45 GHz are performed. Dynamic phase control is also demonstrated by applying a square wave to the phase section of the laser, thereby phase modulating the 45 GHz subcarrier. Good AM suppression is observed. Demonstration of dynamic phase control is a significant step towards realizing simple mm-wave optical transmitters with electronically programmable phase control for beam-steering in narrowband phased-array antenna networks.

TH 3D

EXPERIMENTAL RESULTS

The laser is a three-section multiple-quantum-well DBR laser fabricated at AT&T Bell

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Laboratories [3] with a total cavity length of approximately 1.2 mm. It is biased for ~2 mW output power and emits at 1.55μm. Details of the device structure can be found in [3]. Modulation response measurements of this device in the vicinity of the intermodal frequency can be found in [4]. To ascertain the RF phase-shifting properties of this device, the intermodal frequency spacing of the device is measured first to be ~ 45 GHz over the entire optical tuning range. To illustrate injection-locking of the noise at the intermodal frequency by an external RF source, Figure 1 below shows the measured photodetected RF spectrum for the DBR laser at 45 GHz for (a) unlocked and, (b) injection-locked conditions.

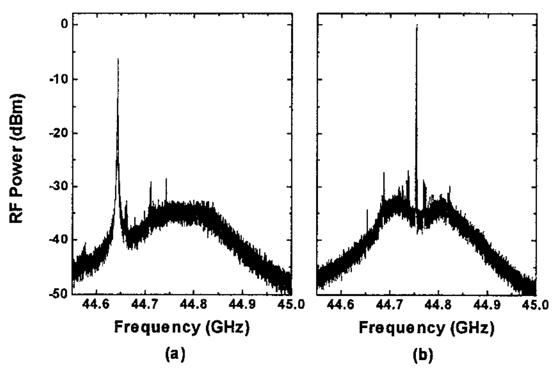

FIGURE 1: Measured RF photodetected spectrum after 2.2 km transmission under (a) unlocked and (b) injection-locked condition. RBW=300kHz.

It is evident from Figure 1(a) that the noise occurring at the round-trip cavity limits the dynamic range of resonantly modulated optical transmitters [2]. However, at sufficient RF drive power, the noise is suppressed by the external 45 GHz modulation as it is tuned towards the center of the noise bump as shown in Figure 1(b), reminiscent of classical injection-locking [5]. It is important to note, however, that the mechanism underlying injection-locking of the DBR laser is fundamentally different from that of two electrical oscillators. Another noteworthy feature of Figure 1(b) is the "gain" experienced by the signal under the injection-locked condition, as compared to resonantly modulated transmitters [2]. The gain experienced by the 45 GHz tone due to injection-locking was measured at ~ 5 dB (over that of resonantly modulated transmitters) at +10 dBm drive power.

To ascertain the RF phase-shifting properties in detail, an 11.2 GHz signal coming from a synthesized signal generator is quadrupled to create a signal at ~45 GHz to injection-lock the laser. The 45 GHz mm-wave tone is efficiently delivered to the gain-contact of the laser with the aid of a single-section microstrip matching circuit that reduces the reflection coefficient of the laser to $|S_{11}|$ = -10 dB over a narrow band centered 45 GHz. The light out of the laser is collimated, passed through an isolator and focused into a single-mode fiber, transmitted over 2.2 km, photodetected and amplified. Figure 2 shows an oscilloscope (BW=50 GHz) measurement of the 45 GHz tone being phase shifted by ~ 140° in response to a 1.4 mA change in the bias current into the phase section.

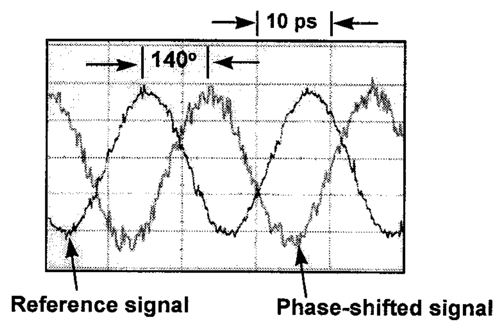

FIGURE 2: Measured oscilloscope trace showing phase-shifting of the output 45 GHz tone after 2.2 km transmission through single-mode fiber.

The measurement was made after 2.2 km of transmission through single-mode fiber. Good fidelity of the phase-shifted 45 GHz subcarrier is observed. Phase shift of the 45 GHz tone over the entire range of phase-section bias currents is accurately measured on the oscilloscope by comparing the phase of the photodetected signal to a photodetected reference. Figure 3 below the detailed phase shift vs. phase-section bias current of the laser for an input RF drive power of ~ +10 dBm.

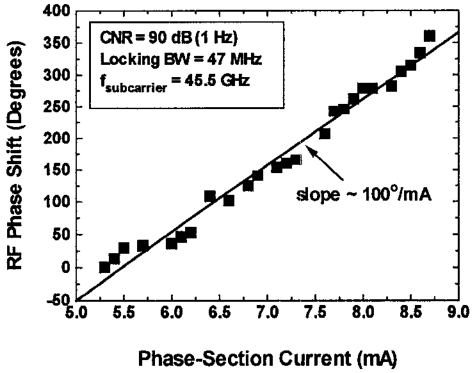

FIGURE 3: Measured RF phase shift of the input 45 GHZ tone as a function of bias current to the phase section of the DBR laser.

Higher RF drive powers lead to a higher degree of linearity and locking bandwidth. A linear regression fit for the data points in Figure 3 reveals a slope of 100°/mA with a standard deviation of 3°/mA and ~20° for the absolute phase. Over the range of bias currents from 6.5 - 7.5 mA, however, the measured phase deviates from linearity by < 10°. A key feature of Figure 3 is the surprising total range of the phase shift obtained with the injection-locked mm-wave optical transmitter when varying the bias current into the phase section of the device. The output mm-wave signal was continuously phase shifted over a range >360°. Over this range, however, some variation in the amplitude of the 45 GHz tone was observed on the oscilloscope. Injection-locking bandwidth for the measurement is ~ 47 MHz at a carrier-to-noise ratio (CNR) of 90 dB (1 Hz). Stability of the signal is also excellent notwithstanding the absence of thermoelectric cooling.

Next, measurements on dynamic phase control of the 45 GHz subcarrier are performed. A bias tee is added to the phase section of the DBR laser to couple the dc bias current and the ac phase-control signal into the phase section of the laser. A 28 mVpp square wave with a pulse repetition frequency of 3 MHz is applied to the phase section, and the output photodetected RF spectrum is observed on a spectrum analyzer after 2.2 km of transmission through single-mode fiber. Figure 4 below shows the photodetected mm-wave spectrum with and without the application of the pulse phase-control signal.

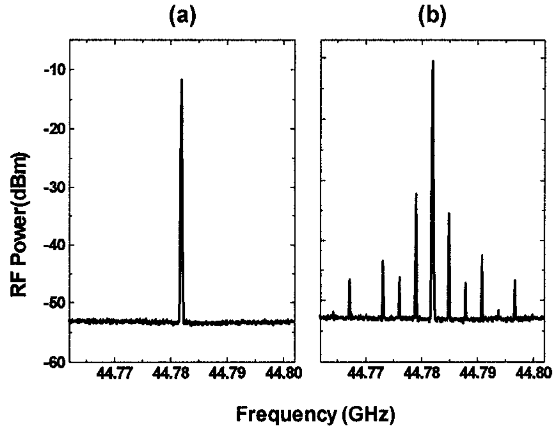

Figure 13. Measured RF spectrum at the output of the detector after 2.2 km fiber transmission without (a) and with (b) phase modulation of the injection-locked mm-wave subcarrier at a periodic rate of 3 MHz. RBW=100 kHz.

Since the intermodal frequency noise is injection locked to the 45 GHz input tone, no frequency modulation (FM) of the subcarrier is generated. The intensity out of the laser is then assumed to take the form

$$L(t) = A(t)\,(1 + a\sin(\omega t+\phi(t))) \qquad (1)$$

For an ideal phase modulated signal, A(t) is constant. To assess the degree of amplitude modulation (AM) A(t) due to the baseband square-wave modulation, the RF spectrum was measured at low frequencies at the output of the photodetector. Comparing the modulation sidebands closest to the 45 GHz subcarrier (3 MHz away) to the first harmonic of the square wave (3 MHz) at baseband reveals that the first harmonic of the modulating square wave is 10 dB down in RF power, indicating that the magnitude of A(t) is small compared to that of ϕ(t). Therefore, modulation of the phase-section of the DBR laser produces a phase modulated RF injection-locked mm-wave subcarrier with good AM suppression. Detailed measurements will be presented.

In conclusion, we have demonstrated continuous linear 360° RF phase control and simultaneous efficient transport over 2.2 km of single-mode fiber of mm-wave signals using monolithic single-frequency semiconductor lasers. This technique provides a means of building simple, compact efficient, cost-effective narrowband mm-wave optical transmitters with dynamic phase-control capability for phased-array and mm-wave personal communication networks.

The authors wish to thank U. Koren and T.L. Koch of Bell Laboratories, Holmdel, N.J. for the lasers.

This work is supported by an Army Phase I contract number DAAL01-95-C-3508.

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