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Performance of Resonant Modulation in the mm-Wave Frequency Range: Multi-Subcarrier Modulation

Optical transmitters capable of efficiently transporting several millimeter-wave (mm-wave) subcarriers to/from fiber-fed antenna sites in indoor/out-door mm-wave mobile/point-to-point wireless networks are of considerable importance in mm-wave free space links [101, 102]. Future deployment of a fiber infrastructure in these systems rests primarily upon the availability of *low-cost* mm-wave optical transmitters. Optical transmission of a *single* narrowband (50 Mb s^{-1}) channel at 45 GHz was demonstrated using resonant modulation of an inexpensive, conventional semiconductor laser with a baseband direct modulation bandwidth of <5 GHz [103]. It was shown that this technique provides a means of building simple, low-cost, narrowband (<1 GHz) mm-wave subcarrier optical transmitters for frequencies approaching 100 GHz. In this chapter, the *multichannel* analog and digital performance of these transmitters at a subcarrier frequency of ∼40 GHz are described. Two-tone dynamic range is characterized in detail as a function of bias to the laser, and a maximum dynamic range of 66 dB-$\text{Hz}^{-2/3}$ is found. Although this is modest by conventional, say, CATV standard, it is adequate for serving a typical indoor picocell with a 40 dB variation in received RF power for a per-user voice channel bandwidth of 30 kHz and a carrier-to-interference ratio of 9 dB. A multichannel system implementation of resonant modulation is also presented in which two signals centered around 41 GHz operating at 2.5 Mb s^{-1} BPSK are transmitted over 400 m of single mode optical fiber. The required RF drive power to the laser to achieve a bit-error-rate (BER) of 10^{-9} for *both* channels transmitting *simultaneously* is measured to be <5 dBm per channel. Based on these transmission results and by taking advantage of conventional wireless time-division multiplexing techniques in which up to eight users can share a single channel [104], these mm-wave links are potentially adequate in remoting signals from an antenna serving up to 16 mobile users in an indoor environment.

The setup used to perform two-tone measurements and multichannel digital transmission test of the mm-wave optical transmitter is illustrated in Fig. 10.1. The laser used was a GaAs quantum-well laser with a cavity length

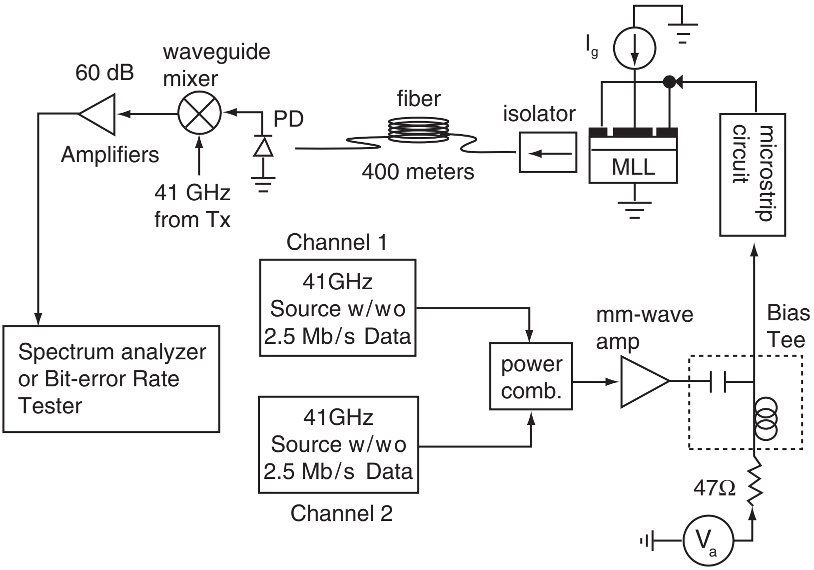

Fig. 10.1. Setup to measure the modulation response at 41 GHz, perform two-tone measurements, and characterize the digital performance of the transmitter (a multi-contact but otherwise conventional laser diode). (From [105], ©1995 IEEE. Reprinted with permission)

of ∼900 μm and emitting at 850 nm. First, the small-signal modulation response at the cavity round-trip frequency is measured. The modulation signal is delivered to the laser with the aid of a single-section microstrip matching circuit having a response shown in Fig. 10.2. The matching circuit reduces the reflection coefficient S_{11} of the laser to −15 dB at 41.15 GHz as measured. Modulation response around 41 GHz is shown in Fig. 10.3 for several bias conditions. By simply adjusting the bias to the laser, a higher modulation efficiency is achieved at the expense of passband bandwidth [103]. At a modulation efficiency of −5 dB (relative to that at dc) the passband bandwidth is ∼200 MHz.

For dynamic range measurements, two mm-wave tones from two Gunn oscillators operating at 41 GHz and separated by ∼1 MHz are electrically power-combined and delivered to the laser. Electrical isolation between the oscillators is >30 dB. The light emitted from the laser is sent through 400 m of single-mode fiber where it is detected, amplified, downconverted to IF and observed on a spectrum analyzer. The resulting dynamic range plots are shown in Fig. 10.4. A comparison of Figs. 10.3 and 10.4 reveals a trade-off between modulation efficiency and dynamic range. A maximum dynamic range of 66 dB-Hz$^{-2/3}$ is obtained for this laser. Note that the IP3 point is comparable to that below relaxation oscillation (∼10 dbm). At a higher modulation efficiency, the dynamic range is reduced to ∼58 dB-Hz$^{-2/3}$ due to the increased, resonantly

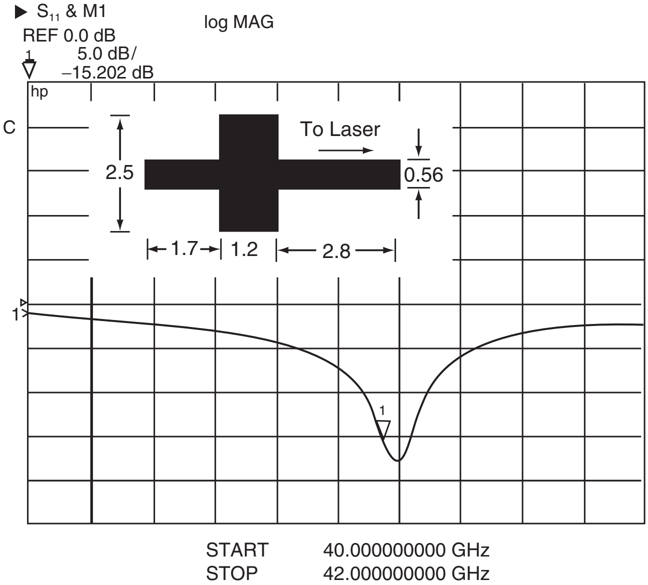

Fig. 10.2. Measured reflection coefficient S_{11} of the combined laser plus matching circuit. The mm-wave matching circuit was fabricated on a 0.18-mm-thick Duroid board with metallization dimensions (in millimeters) shown in the *inset*. (From [105], ©1995 IEEE. Reprinted with permission)

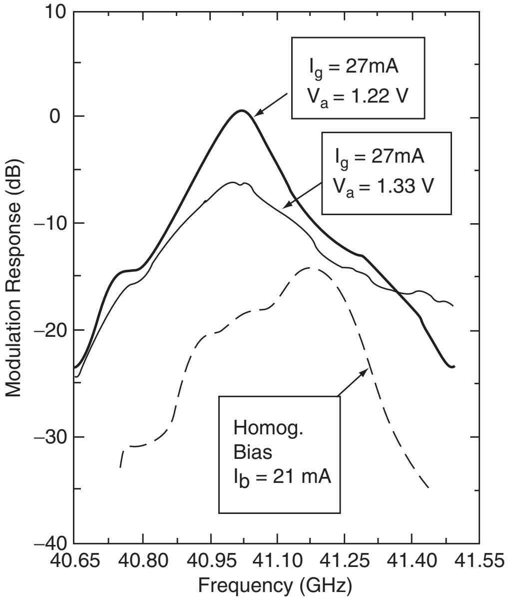

Fig. 10.3. Measured small-signal modulation response at the cavity round-trip resonant frequency of 41 GHz for various bias conditions. The vertical axis is relative to that of the dc of $0.26\,\mathrm{W\,A^{-1}}$. (From [105], ©1995 IEEE. Reprinted with permission)

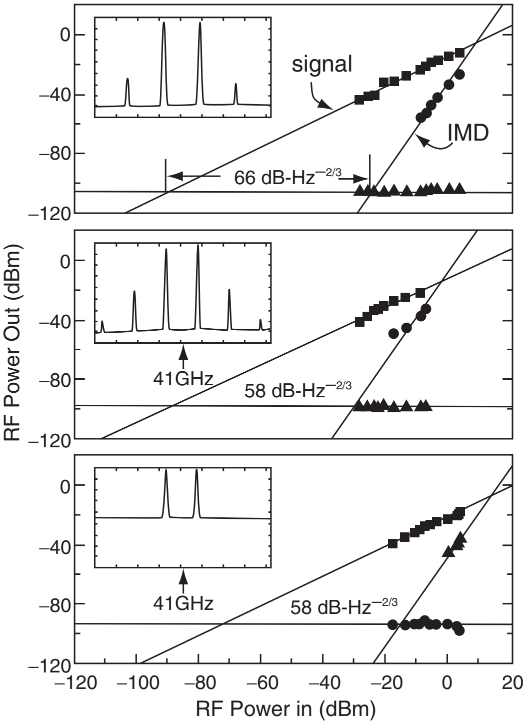

Fig. 10.4. Measured two-tone dynamic range under the same bias conditions used to obtain the modulation response measurements in Fig. 10.1. The *top figure* is for the bias condition $I_\mathrm{g} = 27\,\mathrm{mA}$, $V_\mathrm{a} = 1.33\,\mathrm{V}$; the *middle figure* $I_\mathrm{g} = 27\,\mathrm{mA}$, $V_\mathrm{a} = 1.22\,\mathrm{V}$; the *bottom* for homogeneous bias $I_\mathrm{b} = 21\,\mathrm{mA}$. The scale for the insets is 5 dB/div. RBW = 1 MHz. (From [105], ©1995 IEEE. Reprinted with permission)

enhanced noise. For homogeneous bias, the distortion level is lower (for the same drive power), but the corresponding high level of noise leads to a low dynamic range (58 dB-Hz$^{-2/3}$). The insets show the measured intermodulation products for each bias condition at an electrical drive power per channel of −6 dBm. No difference was observed when the dynamic range measurements were repeated for the same bias conditions in the absence of the 400 m of fiber, which suggests the dynamic range was limited by the laser. Improvement in the dynamic range can be achieved (at the expense of modulation efficiency) by incorporating intracavity frequency selective elements such as gratings or coupled cavities [106].

Next, the performance of the transmitter modulated by two binary-phase shift-keyed (BPSK) subcarrier channels is ascertained. The laser is biased for a modulation efficiency of ∼0 dB (relative to dc), a passband bandwidth of ∼200 MHz, and emitting an optical power of ∼2 mW. Two channels each transmitting pseudorandom ($2^9 - 1$) return-to-zero data at $2.5\,\mathrm{Mb\,s^{-1}}$ are

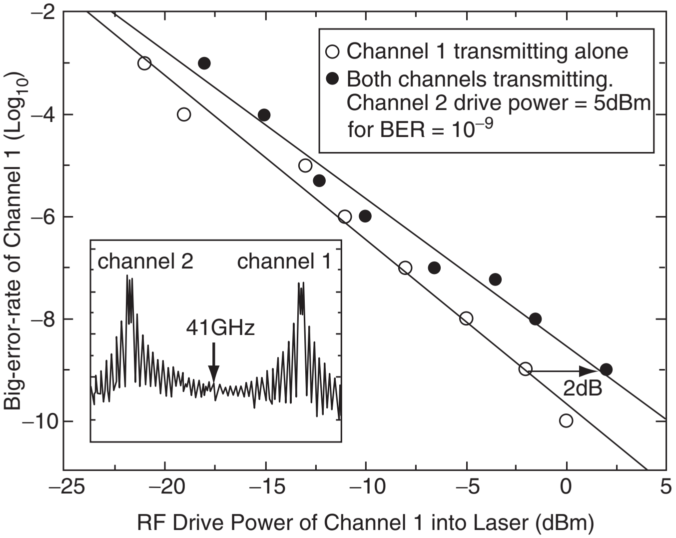

Fig. 10.5. Bit-error-rate of channel 1 as a function of RF drive power of channel 1 with and without the presence of channel 2 for 2.5 Mb s^{-1} retum-to-zero BPSK modulation centered around 41 GHz. The *inset* shows the received RF spectrum of both channels transmitting simultaneously after transmission over 600 m of single-mode optical fiber. The inset scale is 5 dB/div. (From [105], ©1995 IEEE. Reprinted with permission.)

upconverted to 41 GHz using a Q-band waveguide mixer and power combined to modulate the laser. The signals are transmitted over 400 m of single-mode fiber. At the receiver, the signals are down-converted to baseband, amplified and sent to an error-rate tester. The BER versus electrical drive power of channel 1 (centered at ∼41.15 GHz) is first measured with channel 2 (centered at ∼40.95 GHz) turned off as shown in Fig. 10.5. The RF power required to achieve a BER of 10^{-9} for this single channel is −2.5 dBm. With channel 2 activated, an additional 2 dB of RF power (power penalty) is required to keep channel 1 operating at 10^{-9}. Likewise, the drive power required for channel 2 to operate at 10^{-9} in the presence of channel 1 is 5 dBm. The difference in RF power between the channels for 10^{-9} operation stems from injection-locking effects which occur under higher RF drive power. Injection locking at channel 1 leads to a higher level of noise at channel 2, as illustrated in the inset of Fig. 10.4. At lower drive powers, both channels act independently as evidenced by the convergence of the BER curves at low drive powers.

The above sections have demonstrated the multichannel analog and digital performance of mm-wave optical transmitters based on resonant modulation of monolithic semiconductor lasers, and have established their feasibility as narrowband optical transmitters in fiber links serving remote antennae in indoor mm-wave wireless microcells. A two-tone dynamic range of 66 dB-$\mathrm{Hz}^{-2/3}$

was obtained at a cavity round-trip frequency of 41 GHz and was limited by the high level of noise. Optical transmission over 400 m of fiber of two simultaneous 2.5 $\mathrm{Mb\,s^{-1}}$ channels centered 41 GHz and operating at <5 dBm RF drive power per channel at a BER of 10^{-9} was also demonstrated.