Signal Generation Using Pulsed Semiconductor Lasers for Application in Millimeter-Wave Wireless Links

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***Abstract*—We investigate the generation of signals using pulsed semiconductor lasers for application in millimeter-wave (mm-wave) wireless links. The generation of mm-wave harmonic frequencies in both mode-locked and gain-switched lasers is considered and a method to generate mm-wave modulated optical signals with modulation depths approaching 100% is implemented. The technique uses optical filtering to select only two optical modes in the pulsed laser spectrum that beat together in a high-speed photodiode. The application of this method to the feeding of mm-wave wireless links incorporating microstrip patch antennas is demonstrated. These optically fed links have application in indoor wireless LAN's and optical fiber microcellular systems.**

I. INTRODUCTION

THE GENERATION of microwave and millimeter-wave (mm-wave) signals using optical techniques is of interest for applications such as optical phased arrays [1], optical fiber feeds and distribution for microcellular mobile [2] and radio [3], [4] communications, and distribution of signals for satellite antennas [5]. More recently, attention has focused on the transmission of mm-wave signals on optical carriers for telecommunication applications, as a result of the allocation of mm-wave frequencies for wireless links to overcome crowding in the lower frequency spectrum [6]. Mobile and personal radio systems at such frequencies also offer the advantages of smaller equipment and antennas. Thus the inherent advantages of optical fiber over coax and waveguide as a transmission medium has led to the consideration of the optical generation and distribution of mm-wave signals. In addition, the commercial development of optical amplifiers with very wide bandwidth means they can be easily incorporated in mm-wave fiber-optic links to provide gain at such frequencies.

At present, state-of-the-art semiconductor lasers exhibit less than 30 GHz bandwidth although the addition of an external cavity enables narrowband modulation beyond the resonant frequency [7], [8]. The drawback, however, of direct modulation at such high frequencies is the requirement of a mm-wave source. Other optical techniques for mm-wave signal generation include optical heterodyne using two laser sources [9], [10] and harmonic generation using either laser nonlinearities [11], external modulators [12] or pulsed semiconductor lasers [13], [14]. Optical heterodyne usually requires locking of at least one laser frequency [15] and since the phase noise of each optical source is uncorrelated, some feedback arrangement is also required to reduce the electrical linewidth of the beat signal [16]. Harmonic generation techniques using only one optical source are less complex to implement, however their disadvantage is the simultaneous presence of unwanted harmonics that limit the achievable modulation depths at the desired frequencies. One solution would be to use an optical amplifier to boost the detected optical power of the desired harmonic frequency. However, the optical gain that can be used is limited because the optical carrier and the optical frequencies close to the carrier add significantly to the average optical power and the detected photocurrent.

We have previously described a novel technique that overcomes the limitations associated with harmonic generation methods since it can be used in conjunction with these techniques to generate mm-wave signals with 100% modulation depth [17]. Unlike optical heterodyne with two sources, the method uses only one optical source and so the phase noise of the laser modes are correlated producing very low phase noise electrical signals without complex circuitry. Our technique uses an optical filter to select only two laser modes separated at the desired mm-wave frequency that beat together in a high-speed photodiode. Our method is therefore a dual mode self-heterodyne technique where the two optical modes are phase-locked together. In this paper we investigate the generation of very high frequency harmonics in both mode-locked and gain-switched semiconductor lasers for application in millimeter-wave wireless links. The two pulsed lasers are described in Section II while Section III presents the implementation of the optical filtering technique. In Section IV we develop some simple theory for our method and show that the rf power improvement observed in Section III increases with laser pulsewidth. Section V then describes optically fed millimeter-wave wireless links that incorporate microstrip patch antennas and the mm-wave signal generation technique presented in Section III. Finally, we present conclusions in Section VI.

II. PULSED SEMICONDUCTOR LASERS

For the generation of mm-wave signals we investigate pulsed semiconductor lasers where the microwave spectrum of the pulsed output is a comb of frequencies with a high

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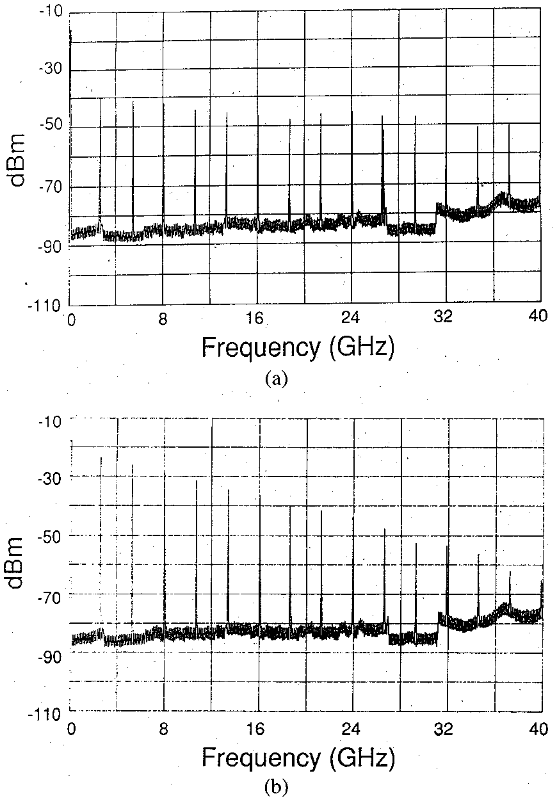

Fig. 1. Microwave spectra of the amplified pulses from (a) MLSL and (b) GSLD (resolution bandwidth—RBW = 1 MHz; video bandwidth—VBW = 10 kHz).

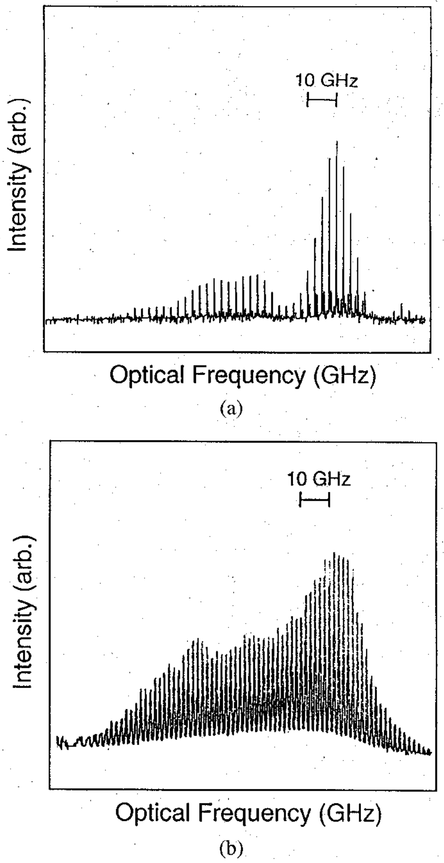

Fig. 2. Measured optical spectra before optical filtering of (a) MLSL and (b) GSLD.

harmonic content [14]. We first consider an actively mode-locked semiconductor laser (MLSL) consisting of a 1.56 μm laser chip with an AR-coated rear facet coupled to a grating-controlled external cavity, 5.6 cm in length [18]. Fundamental mode-locking was achieved by supplying a +28 dBm rf signal at 2.65 GHz to the laser via a bias tee. At the MLSL output an isolator with >70 dB isolation eliminates feedback into the laser before coupling into single-mode fiber. We next investigate a gain-switched laser diode (GSLD) consisting of a 1.55 μm quantum-well $\lambda/4$-shifted DFB laser with >10 GHz bandwidth. Gain-switching is usually simpler to implement than mode-locking because precise optical alignment is not necessary. The laser is gain-switched with a +28 dBm signal at 2.65 GHz and the output also coupled into fiber after a 60 dB isolator.

The detected laser pulses were observed on a sampling oscilloscope and the widths of the MLSL and GSLD pulses after deconvolving with the instrument response were 15 ps and 34 ps, respectively. The microwave spectra of the pulsed laser outputs, measured using a 45 GHz bandwidth photodiode and a 40 GHz spectrum analyzer, are shown in Fig. 1. Since the lasers' output powers were relatively low and further reduced after fiber coupling, a low-noise erbium-doped fiber amplifier (EDFA) with 16 dB gain was used to boost the pulsed outputs before detection. Harmonic frequencies up to 37.1 GHz (= 14th harmonic) are observed in both spectra. For the MLSL [(Fig. 1(a)], the post-detection rf power at 2.65 GHz was −40 dBm with the power in the harmonics decreasing to −51 dBm at 37.1 GHz. Fig. 1(b) shows the rf power of the fundamental frequency in the GSLD was around −23 dBm with −62.5 dBm at 37.1 GHz. The larger rf power at 2.65 GHz for the GSLD is due to the larger optical output power from the DFB laser.

III. MILLIMETER-WAVE SIGNAL GENERATION TECHNIQUE

This section describes the technique that has been developed to generate mm-wave modulated optical signals with 100% modulation depth. Fig. 2 shows the optical spectra of the pulsed lasers measured using a high-resolution scanning Fabry-Perot etalon. The MLSL spectrum [(Fig. 2(a)] is symmetrical around the carrier, however another chip mode is also evident due to the long length of the device (500 μm) and the large optical bandwidth of the system. The optical spectrum of the GSLD [(Fig. 2(b)] displays a chirp-induced fine structure that cannot be resolved by the scanning etalon. Fig. 3 shows the experimental setup of the optical filtering technique. The amplified laser output is passed through a Fabry-Perot (FP) interferometer with variable free spectral range (FSR). The FSR was set to 37.1 GHz and the FP tuned to select two laser modes with near equal optical power. The two selected modes are amplified with an EDFA ($\approx$16 dB) gain and beat together in the 45 GHz photodiode. A 1.5 nm bandpass filter (BPF) removes unwanted ASE noise introduced by the EDFA. The second EDFA was necessary in our experiment due to the large insertion loss of the bulk-type FP ($\approx$20 dB). The use

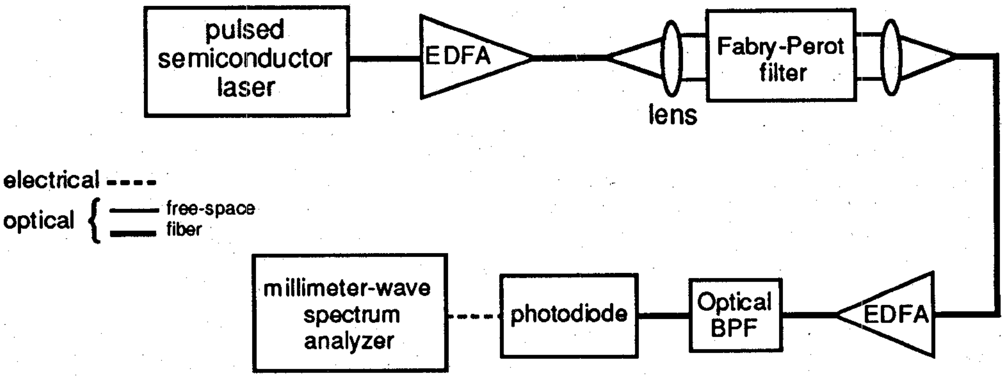

Fig. 3. Block diagram of experimental setup of optical filtering method used with pulsed semiconductor lasers.

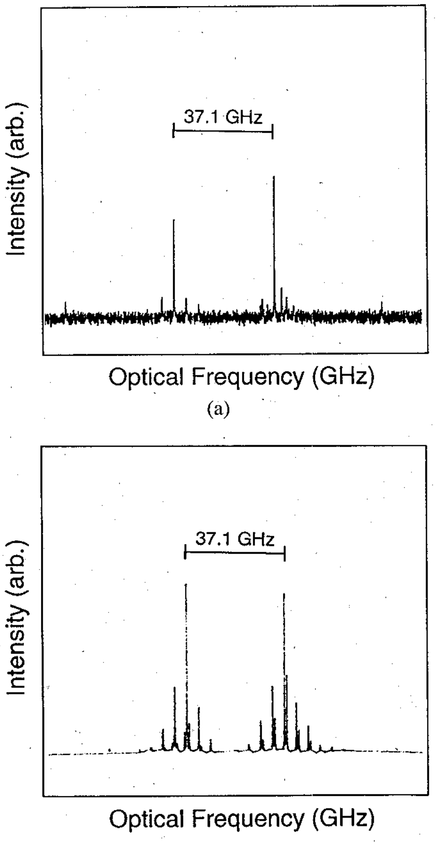

Fig. 4. Measured optical spectra after optical filtering of (a) MLSL and (b) GSLD.

of pigtailed lasers in combination with a fiber FP filter with insertion loss less than 5 dB would avoid the necessity of two EDFA's and minimize the gain required from one.

Fig. 4 shows the measured optical spectra of the pulsed lasers after optical filtering while Fig. 5 displays the microwave spectra of the beat signals at 37.1 GHz. In Fig. 5(a) (MLSL), a very small mixing product at 34.45 GHz can also be seen due to the limited out-of-band attenuation of the FP. This is also evident in the MLSL optical spectrum shown in Fig. 4(a). The GSLD rf spectrum [(Fig. 5(b)] shows several low frequency signals (<1 GHz) although the corresponding optical frequencies in the laser spectrum cannot been seen due to the limited interferometer resolution. The so-called "ghost modes," which can be seen in Fig. 4(b), are instead due to imperfect alignment of the etalon. The phase noises of the MLSL and GSLD beat signals at 37.1 GHz were measured as −75 and −70 dBc/Hz at 5 kHz offsets, respectively. Measurements at larger offsets were −85 dBc/Hz and −75 dBc/Hz for the MLSL and GSLD at 50 kHz, respectively, and −90 dBc/Hz and −80 dBc/Hz at 100 MHz, respectively. The phase noise of the harmonics generated by pulsed lasers is limited by the phase noise of the synthesizer at 2.65 GHz (−80 dBc/Hz at 5 kHz offset) as well as the up-conversion of low-frequency synthesizer noise, [19].

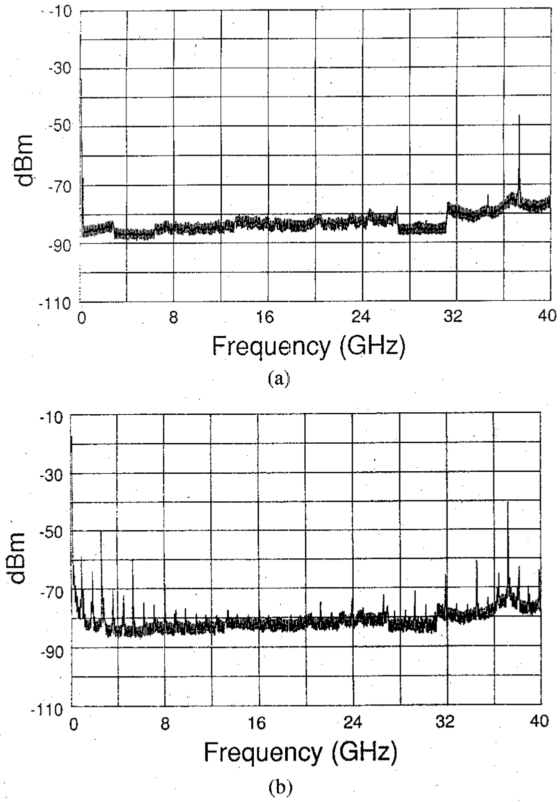

Fig. 5. Microwave spectra after optical filtering of (a) MLSL and (b) GSLD (RBW = 1 MHz, VBW = 10 kHz).

For the results shown in Fig. 5, the gain of the second EDFA was adjusted to give the same average photodiode currents as for Fig. 1. Comparing the post-detection rf power at 37.1 GHz in Fig. 1(a) (−51 dBm) and Fig. 5(a) (−46 dBm) shows an improvement of 5 dB for the MLSL. A similar comparison of Figs. 1(b) and 5(b) for the GSLD gives an rf power improvement with optical filtering of 22 dB, much larger than that observed for the MLSL. The next section investigates this difference.

IV. ANALYSIS OF OPTICAL FILTERING TECHNIQUE

This section develops a simple theory to explain the observed improvement in post-detection rf power after optical filtering of a pulsed laser. If the laser pulses are Gaussian, a comb of frequencies will be generated after detection with an ideal photodiode [14]

$$P_{\mathrm{NF}}(f) = 2R_L(\mathcal{R}P_{\mathrm{oavg}})^2 e^{-(2\pi T_o f)^2} \tag{1}$$

where P_{NF} is the electrical power at harmonic frequency f when no optical filtering is present, $P_{o\mathrm{avg}}$ is the average optical power, T is the pulse repetition rate, T_o is the Gaussian pulse time constant, R_L is the photodiode load resistance, and $\mathcal{R}$ is the photodiode responsivity. P_{NF} can also be expressed as a function of the optical power $P_{o\mathrm{NF}}$

$$P_{\mathrm{NF}} = \frac{1}{2}R_L[\mathcal{R}P_{o\mathrm{NF}}]^2 \tag{2}$$

We derive the relationship between T_o and the pulse width at half-maximum τ, substitute for T_o in (1) and equate (1) and (2) to get an expression for the optical modulation depth at harmonic frequency f with no optical filtering

$$\frac{P_{o\mathrm{NF}}}{P_{o\mathrm{avg}}} = \frac{2}{\exp[2.67\tau f]}. \tag{3}$$

As expected, (3) indicates that the optical modulation depth at a particular frequency will decrease with wider laser pulses and at higher harmonic frequencies. We can now derive an expression for the improvement in post-detection rf power RF_I with optical filtering, which is defined as

$$\mathrm{RF}_I\ (\mathrm{dB}) = 20\log\frac{P_{oF}}{P_{o\mathrm{NF}}} \tag{4}$$

where P_{oF} is the optical power at harmonic frequency f with optical filtering. Only two laser modes are selected with optical filtering which beat together to give f, thus the optical modulation depth is 100%. Therefore, $P_{oF} = P_{o\mathrm{avg}}$ and from (3), the rf power improvement for the same average photodiode current is

$$\mathrm{RF}_I\ (\mathrm{dB}) = 20\log\frac{\exp[2.67\tau f]}{2}. \tag{5}$$

Fig. 6 shows the calculated rf power improvement as a function of harmonic frequency for several laser pulsewidths. For the MLSL with 15 ps pulses, a value of $\mathrm{RF}_I = 6.8$ dB at 37.1 GHz is predicted, very close to the measured value of 5 dB. A similar calculation for the GSLD gives $\mathrm{RF}_I = 23.2$ dB, which is close to the measured value of 22.0 dB. Fig. 6 shows that for a particular laser pulsewidth, the rf power improvement increases linearly with harmonic frequency and is significantly higher at mm-wave frequencies. Also, RF_I is larger with wider laser pulses. With no optical filtering of a pulsed laser, minimum pulsewidths are required to achieve maximum rf power at the desired frequency. However if optical filtering and amplification is introduced, the width of the laser pulses is no longer critical and the pulsed lasers need not be optimized for minimum pulsewidth, although more optical gain is required to boost the lower power harmonics that occur with wider pulses.

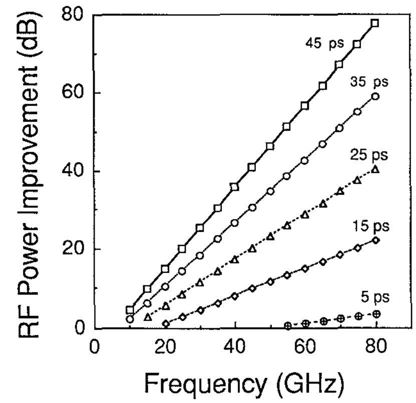

Fig. 6. Calculated improvement in post-detection rf power using optical filtering in conjunction with a pulsed laser, shown as a function of harmonic frequency for several values of laser pulsewidth.

V. MILLIMETER-WAVE RADIO LINK DESIGN

This section describes the implementation of an optically fed mm-wave wireless link suitable for microcellular and indoor wireless systems, which generally require antennas that are low cost, unobtrusive, and have broad beamwidths. Microstrip patches are considered for this application as they possess such features and can be easily integrated with photonic/MMIC devices. We also incorporate probe-fed microstrip patches due to lower loss associated with this feeding mechanism and thus higher antenna efficiency. The mm-wave microstrip patches were designed using a rigorous full-wave analysis based on the spectral domain Electric Field Integral Equation technique [20]. Two identical circular patches with 1.46 mm radius were etched on a grounded substrate of height 0.254 mm and $\varepsilon_r = 2.22$. The probe feed with K-connector was located at 0.42 mm from the center of each patch to give a 50 Ω resonance at 37.1 GHz and a 10 dB return loss bandwidth of 1.55 GHz. The measured resonant frequency and 10 dB return loss were 37.07 and 1.77 GHz, respectively. The efficiency of the patches (taking into account surface-wave excitation) was 90.5% and the directive gain was calculated as 5.7 dB.

Fig. 7 shows the experimental setup of the optically fed mm-wave wireless link. One antenna was connected to the K-connector of the high-speed photodiode and the other to the spectrum analyzer. Using the MLSL with rf power at 37.1 GHz equal to −46 dBm, the measured received power was −110 dBm after a distance of 2 m. This compares favorably with the predicted value of −105 dBm using the Friis power transmission formula. For the GSLD, the rf power at 37.1 GHz after optical filtering was −40.5 dBm as shown in Fig. 5(b). With both EDFA's in Fig. 7 set at full gain the optical power of the two GSLD modes was further increased to give an rf power of −30 dBm at the photodiode output. After a transmission

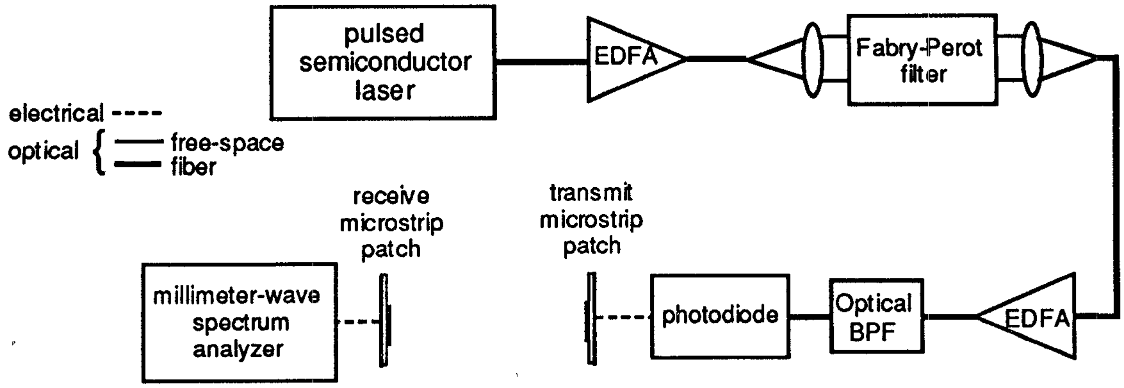

Fig. 7. Experimental setup of optically fed millimeter-wave wireless link.

distance of 3 m, the measured received power was −95 dBm, which is close to the predicted power of −92.8 dBm.

One important contribution to the total loss associated with the optically fed mm-wave links is the coupling of the rf power at the photodiode output to a suitable transmission medium. In this experiment, the microstrip patch dimensions and probe-feed position were optimized for 50 Ω resonance at 37.1 GHz. Typically a photodiode has a small effective resistance and a parasitic reactance associated with the device mounting and packaging. The photodiode used in our link did not incorporate any form of matching structure and an increase in the post-detection rf power of up to 5 dB could be expected if such a circuit was implemented. We are currently investigating techniques for efficiently coupling high speed photodiodes to microstrip patch radiators.

VI. CONCLUSION

We have investigated the generation of signals using pulsed semiconductor lasers for application in millimeter-wave wireless links. An actively mode-locked laser and gain-switched laser generating 15 ps and 34 ps pulses, respectively, were considered and a technique to generate mm-wave modulated optical signals with modulation depths of 100% was implemented with both lasers. The method uses an optical filter to select only two optical modes in the pulsed laser spectrum which beat together in a high-speed photodiode. The advantage of our method over optical heterodyne with two sources is that very narrow electrical linewidths can be achieved without any feedback arrangement since the laser modes are phase-locked. The phase noises of the generated beat signals at 37.1 GHz were measured as −75 dBc/Hz and −70 dBc/Hz at 5 kHz offsets for the MLSL and GSLD, respectively. The rf powers of the beat signals after optical filtering were measured at the same average photodiode current before filtering of the laser outputs. Improvements in the post-detection rf power at 37.1 GHz of 5 and 22 dB were measured for the MLSL and GSLD, respectively. These values were close to calculations predicted by a simple theoretical analysis. The analysis also showed that even greater rf power improvement is possible at higher frequencies and when the laser pulses are wider. The application of the optical filtering method to the feeding of mm-wave wireless links incorporating microstrip patch antennas was demonstrated using both pulsed lasers. Future work will investigate techniques for efficiently coupling high speed photodiodes to the microstrip patch radiators.

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REFERENCES

[1] W. Ng, A. A. Walston, G. L. Tangonan, J. J. Lee, I. L. Newberg, and N. Bernstein, "The first demonstration of an optically steered microwave phased array antenna using true-time-delay," *J. Lightwave Technol.*, vol. 9, pp. 1124–1131, 1991.

[2] Special Issue on Fiber-Optic Microcellular Radio Communication Systems and Their Technologies, *IEICE Trans. Commun.*, vol. E76B, Sept. 1993.

[3] D. Wake, I. C. Smith, N. G. Walker, I. D. Henning, and R. D. Carver, "Video transmission over a 40 GHz radio-fiber link," *Electron. Lett.*, vol. 28, pp. 2024–2025, Oct. 1992.

[4] H. Schmuck, R. Heidemann, and R. Hofstetter, "Distribution of 60 GHz signals to more than 1000 base stations," *Electron. Lett.*, vol. 30, pp. 59–60, Jan. 1994.

[5] A. S. Daryoush, E. Ackerman, R. Saedi, R. Kunath, and K. Shalkhauser, "High-speed fiber-optic links for distribution of satellite traffic," *IEEE Trans. Microwave Theory Tech.*, vol. 38, pp. 510–517, May 1990.

[6] J. Burns, "The application of millimeter-wave technology for personal communication networks in the United Kingdom and Europe," in *Dig. Micro. Th. Tech. Symp.*, San Diego, 1994, pp. 635–638.

[7] R. Nagarajan, S. Levy, and J. E. Bowers, "Millimeter-wave narrow-band optical fiber links using external cavity semiconductor lasers," *J. Lightwave Technol.*, vol. 12, pp. 127–136, Jan. 1994.

[8] J. B. Georges, M. H. Kiang, K. Heppell, M. Sayed, and K. Y. Lau, "Optical transmission of narrow-band millimeter-wave signals by resonant modulation of monolithic semiconductor lasers," *IEEE Photon. Technol. Lett.*, vol. 6, pp. 568–570, Apr. 1994.

[9] G. J. Simonis and K. G. Purchase, "Optical generation, distribution, and control of microwaves using laser heterodyne," *IEEE Trans. Microwave Theory Tech.*, vol. 38, pp. 667–669, May 1990.

[10] L. Goldberg, R. D. Esman, and K. J. Williams, "Generation and control of microwave signals by optical techniques," *IEEE Proc., pt. J*, vol. 139, pp. 288–295, Aug. 1992.

[11] H. Ogawa and Y. Kamiya, "Fiber-optic microwave transmission using harmonic laser mixing, optoelectronic mixing, and optically pumped mixing," *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 2045–2051, Dec. 1991.

[12] J. O'Reilly and P. Lane, "Remote delivery of video services using mm-waves and optics," *J. Lightwave Technol.*, vol. 12, pp. 369–375, Feb. 1994.

[13] K. Y. Lau, "Short-pulse and high-frequency signal generation in semiconductor lasers," *J. Lightwave Technol.*, vol. 7, pp. 400–419, Feb. 1989.

[14] R. J. Helkey, D. J. Derickson, A. Mars, J. G. Wasserbauer, and J. E. Bowers, "Millimeter-wave signal generation using semiconductor diode lasers," *Micro. Opt. Technol. Lett.*, vol. 6, pp. 1–5, Jan. 1993.

[15] A. J. Seeds and A. A. A. de Salles, "Optical control of microwave semiconductor devices," *IEEE Trans. Microwave Theory Tech.*, vol. 38, pp. 577–585, May 1990.

[16] O. Solgaard, J. Park, J. B. Georges, P. K. Pepeljugoski, and K. Y. Lau, "Millimeter-wave, multigigahertz optical modulation by feedforward phase noise compensation of a beat note generated by photomixing of two laser diodes," *IEEE Photon. Technol. Lett.*, vol. 5, pp. 574–577, May 1993.

[17] D. Novak and R. S. Tucker, "Novel technique for millimeter-wave signal generation using pulsed semiconductor lasers," *Electron. Lett.*, vol. 30, pp. 1430–1431, Aug. 1994.

[18] Z. Ahmed, L. Zhai, A. J. Lowery, N. Onodera, and R. S. Tucker, "Locking bandwidth of actively-mode-locked semiconductor lasers," *IEEE J. Quantum Electron.*, vol. 29, pp. 1714–1721, June 1993.

[19] C. R. Lima and P. A. Davies, "Effects of extra low-frequency noise injection on microwave signals generated by a gain-switched semiconductor laser," *Appl. Phys. Lett.*, vol. 65, pp. 950–952, Aug. 1994.

[20] J. T. Aberle and D. M. Pozar, "Accurate and versatile solutions for probe-fed microstrip patch antennas and arrays," *Electromagn.*, vol. 11, pp. 1–19, Jan. 1991.

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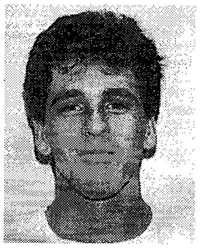

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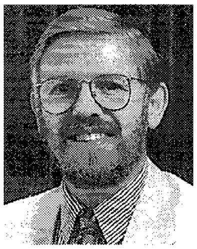

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