37-GHz Fiber-Wireless System for Distribution of Broad-Band Signals

Zaheer Ahmed, Dalma Novak, *Member, IEEE*, Rod B. Waterhouse, *Member, IEEE*, and Hai-Feng Liu, *Member, IEEE*

***Abstract*— We present a millimeter (mm)-wave fiber-wireless system suitable for the transport and distribution of broad-band signals. We show transmission over fiber and wireless distribution of subcarrier multiplexed amplitude-modulation vestigial-sideband (AM-VSB) video and a digital data stream at 37 GHz using optical carriers generated by a hybrid mode-locked laser (HMLL). We also present a simple model to characterize the effect of fiber chromatic dispersion on the transport of millimeter-wave (mm-wave) modulated signals over fiber, and calculations show that by using an HMLL, broad-band signals can be transported successfully over fiber lengths greater than 150 km using subcarrier frequencies <1 GHz and more than 50 km for subcarrier frequencies <3 GHz.**

***Index Terms*— Millimeter-wave lasers, millimeter-wave radio communication, subcarrier multiplexing.**

I. Introduction

DESIGN of broad-band access networks to deliver services such as video-on-demand, interactive multimedia, high-speed internet, and high-density television (HDTV) to homes and industrial and educational institutions has been a subject of intense interest in recent years. Both wireline, i.e., hybrid-fiber-coax (HFC) and wireless [i.e., microwave-multipoint-distribution-system (MMDS)] access techniques show considerable potential in this regard. These access schemes mainly utilize the lower microwave frequency spectrum (< 5 GHz) for distribution of broad-band signals; however, recently the millimeter-wave (mm-wave) frequency band (26–70 GHz) has been considered for wireless access, primarily to avoid spectral congestion at lower microwave frequencies and to offer large transmission bandwidth. Operation at mm-wave frequencies also ensures smaller cells due to large atmospheric absorption giving a large frequency reuse factor for efficient spectrum utilization.

Future mm-wave broad-band access systems may employ an architecture in which signals generated at a central location will be transported to remote base-stations for wireless distribution [1]. Optical feeding of base-stations in these systems is an attractive approach because it enables a large number of base-stations to share the transmitting and processing equipment located remotely from the customer-serving area. In such systems, mm-wave signals can be generated and modulated using optical techniques and transported to base-stations very efficiently via low cost, low loss, and EMI-free optical fibers. Together with high-speed photodetectors (PD's) integrated with mixers, amplifiers, diplexers (using monolithic-microwave integrated-circuit (MMIC) technology) and printed antennas, simple and lightweight base-stations can be designed to allow easy installation on building walls and corners, street lights, and telephone poles.

A number of techniques for the generation, modulation, and distribution of mm-wave modulated optical carriers for fiber-wireless systems have been described in the literature [2]–[14]. Research efforts have also been directed toward exploring the effects of fiber chromatic dispersion on the transport of mm-wave modulated optical signals over fiber [15]–[19]. Fiber chromatic dispersion may induce severe power degradation in the detected RF power of the mm-wave signal after propagation through longer lengths of fiber [15]–[19]. We have recently shown that a passively mode-locked monolithic distributed Bragg reflector (DBR) laser can generate ultra low-noise mm-wave optical carriers by adopting synchronous (optical injection) or hybrid (electrical injection) mode-locking schemes [12], [20]. In this paper we describe the use of a hybrid mode-locked laser (HMLL) to design a mm-wave fiber-wireless system suitable for the distribution of broad-band signals. Attempts toward implementing mm-wave signal distribution schemes have so far considered systems transmitting either digital data or video signals [2], [3], [6], [9], [11], [12]–[14]; however, future interactive multimedia applications would require simultaneous transmission and distribution of data and video. In this paper, we demonstrate for the first time subcarrier multiplexing (SCM) of three composite video channels with 255-Mb/s digital data, subsequent transmission over fiber, and wireless distribution using microstrip patch antennas. We also analyze the effect of fiber chromatic dispersion on the transport of mm-wave modulated signals using this laser. Our analysis shows that the mm-wave modulated carriers produced by an HMLL can be used to transport signals over fiber distances greater than 150 km.

II. MM-Wave Fiber-Wireless System Incorporating an HMLL

Fig. 1 shows the experimental setup for the implementation of the downstream portion of a mm-wave fiber-wireless system. Millimeter-wave optical carriers were generated using a five-section monolithic DBR laser comprising two gain sections, saturable absorber (SA), DBR, and phase-control

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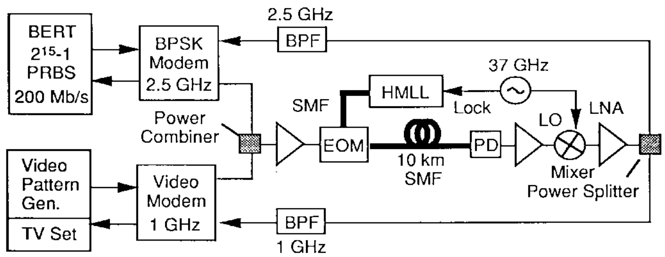

Fig. 1. Experimental setup for the mm-wave transport system incorporating an HMLL ($P_{\rm HMLL} = -3$ dBm, EOM insertion loss $= 4$ dB, fiber-coupling efficiency $= 20\%$, fiber loss $= 0.2$ dB/km, post-detection RF power $= -54$ dBm).

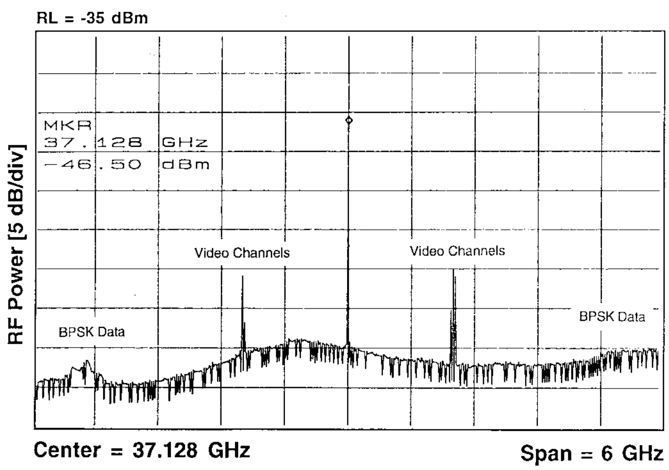

Fig. 2. RF spectrum of the detected mm-wave modulated signal at the output of EOM (RBW equals 1 MHz).

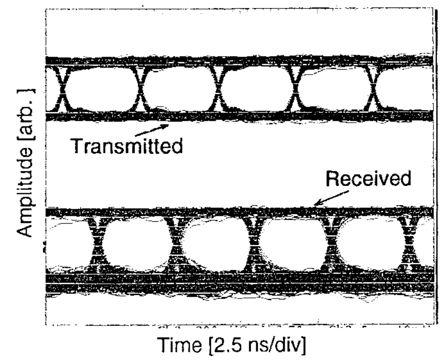

Fig. 3. Eye diagrams of the transmitted (top) and received (bottom) PRBS at 200 Mb/s for $\mathrm{BER} = 10^{-9}$ after transmission through 10 km of fiber.

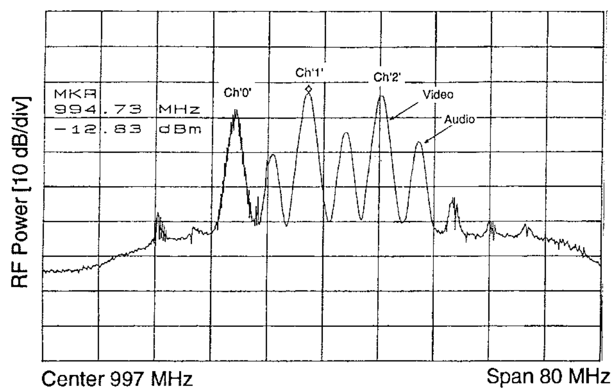

Fig. 4. RF spectrum of the received video channels after 10-km SMF at the input of the video modem (RBW equals 1 MHz).

(PC) regions. The gain sections of the laser were supplied with dc-bias currents of 43 and 94 mA with the DBR and PC sections left with open-circuit terminations. With no dc bias applied to the SA, the laser was passively mode locked and generated a 37-GHz repetition-rate pulse train exhibiting considerable amplitude noise and timing jitter. By applying a $+4$ dBm RF signal at a frequency of approximately 37 GHz to the SA, the laser output became locked to the RF-signal frequency and its phase noise reduced to -85 dBc/Hz at 100-kHz offset frequency. Under these conditions, the device is an HMLL [12].

We employed SCM techniques to simultaneously transmit analog video and digital data [21]. To demonstrate the operation of our system, three composite amplitude-modulation vestigial-sideband (AM-VSB) video channels (channels 0–2), obtained from three video modulators were upconverted in the video modem using a 1-GHz subcarrier. The digital data stream [255-Mb/s nonreturn to zero (NRZ) $2^{15} - 1$ pseudo-random binary sequence (PRBS)] was generated by the transmitter of a bit-error-rate-testset (BERT) and modulated the phase of a 2.5-GHz subcarrier in the BPSK format. The upconverted video channels and the BPSK data signals were then power combined, amplified, and used to modulate the output of the HMLL via a Mach–Zehnder electro-optic intensity modulator (EOM). Each mode of the optical spectrum of the HMLL is modulated by the SCM signal. Fig. 2 shows the RF spectrum of the detected mm-wave modulated optical signal at the output of the EOM. Note that the carriers at 34.5 and 39.5 GHz with an optical modulation depth of approximately 0.3% correspond to the BPSK data signal. The video carriers with a modulation depth of approximately 3% appear at 36 and 38 GHz.

The performance of the downstream link was measured as follows. The mm-wave modulated optical signal was amplified using an erbium-doped fiber-amplifier (gain equals 12 dB) and launched into 10 km of standard single-mode fiber (SMF). At the end of the fiber, the optical signal was detected with a 45-GHz bandwidth (BW) PD, amplified by a low-noise amplifier (LNA), and directed to a Ka-band waveguide mixer to extract the SCM signal. In this experimental demonstration, we have not implemented carrier recovery of the received signal, and the local oscillator (LO) to the mixer was derived from a portion of the 37-GHz signal which stabilizes the HMLL. After suitable amplification, the SCM signal was split and the upconverted video and the BPSK data were separated using narrow-bandpass filters centered at 1 and 2.5 GHz. The baseband data stream and composite video channels were recovered in the BPSK/video modems. Fig. 3 shows the eye diagrams of the recovered PRBS for a BER $<10^{-9}$ at a received optical power of -8 dBm. The additional noise on the zeros is due to the mixer used to generate the 2.5-GHz BPSK data and is present with no optical path between the electrical transmitter and receiver. Fig. 4 shows the recovered composite video channels with a measured baseband weighted SNR of

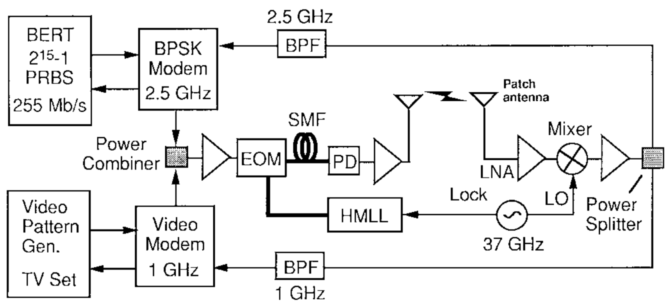

Fig. 5. Experimental setup for the mm-wave fiber-wireless distribution system.

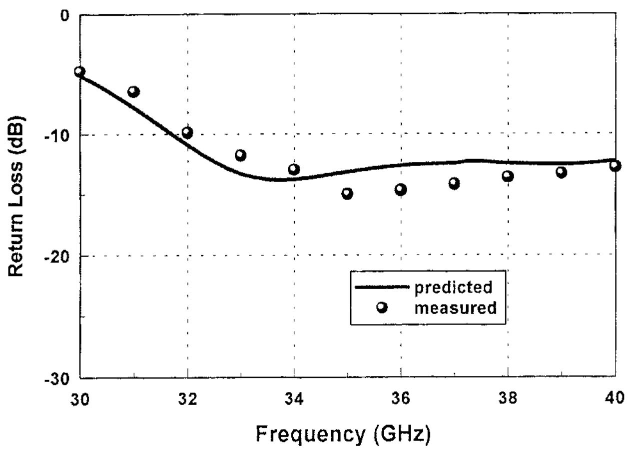

Fig. 6. Predicted and measured return loss of the designed printed antennas.

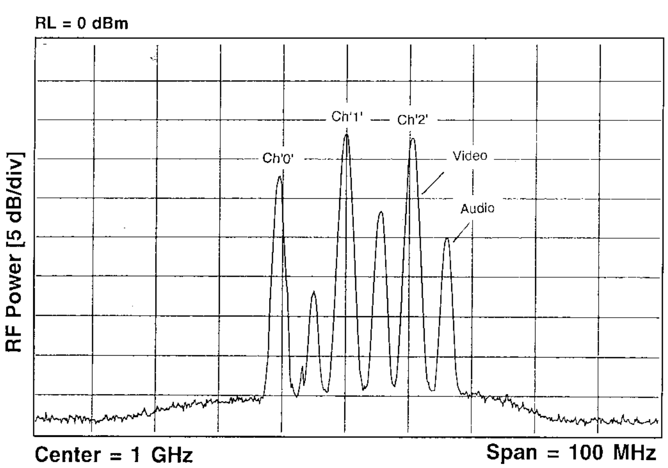

Fig. 7. RF spectrum of the received video channels after the wireless link at the input of the video modem (RBW equals 1 MHz).

43.4 dB. This favorably compares with the weighted SNR of 46.4 dB on the International Radio Consultative Committee CCIR impairment rating scale of 4.5 (close to imperceptible) [22].

We next evaluated the performance of a wireless link as shown in Fig. 5. The mm-wave modulated optical signal was directed to the base-station which comprised the PD, 26–40-GHz BW amplifier (gain $\sim$ 55 dB), and a broad-band aperture-coupled microstrip patch antenna designed for our experiment. The antenna structure comprises a large slot in the ground

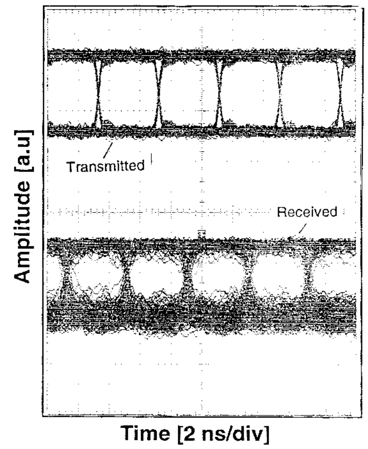

Fig. 8. Eye diagrams of the transmitted (top) and received (bottom) PRBS at 255 Mb/s for BER $= 10^{-9}$ after 1-m wireless transmission.

plane to couple the microstrip feed line to the patch antenna using an electrically thick antenna substrate. Fig. 6 shows the predicted and measured return loss of the aperture-coupled patch and shows a 10-dB return loss bandwidth of 10 GHz centered at 37 GHz. The patch had a predicted gain of 7 dB. An identical patch was placed at a distance of 1 m to receive the radiated signal. Using suitable amplification after the receive antenna to compensate for the propagation loss, the mm-wave signal was downconverted by the mixer and the video channels and the data were recovered as described earlier. Fig. 7 shows the downconverted video spectrum exhibiting a baseband-video weighted SNR of 39.4 dB. It is evident that the mm-wave wireless link incurs a penalty in the received video-signal SNR due to the requirement of additional mm-wave amplifiers to boost the signal before downconversion. Fig. 8 shows the eye diagram of the recovered PRBS at 255 Mb/s for a BER of 10^{-9}.

III. Effect of Fiber Chromatic Dispersion

It is well known that fiber chromatic dispersion limits the transmission distance in direct-detection optical-communication systems [23], [24]. The lower sidebands (LSB's) and upper sidebands (USB's) of the modulating data signal carried by an optical carrier at 1550 nm undergo phase shifts (due to the wavelength dependence of the mode propagation speed) as they propagate down the fiber. At the receiver, the USB's and LSB's beat with the optical carrier to yield the original data signal. However, depending on the fiber length, chromatic dispersion parameter, and modulation frequency, the relative phase difference between the LSB and the USB of the data signal at the receiver can become 180°, resulting in complete cancellation of the beat signal. In mm-wave fiber-wireless systems, the effect becomes even more pronounced and the fiber transmission distance is severely limited [15]–[18].

In this section, we model the effect of fiber chromatic dispersion on data transmission using the optical carriers produced by the HMLL. The HMLL produces an optical spectrum which is essentially dual moded with mode spacing equal to 37 GHz. The mm-wave optical signal can, therefore, be expressed as electric field

$$E(t) = P\{\sin(\omega_0 + \omega_m)t + \sin(\omega_0 - \omega_m)t\} \tag{1}$$

where E is the output field, P is a constant describing the mode intensity, ω_0 is the central frequency of the spectrum, and $2\omega_m$ is the repetition frequency of the HMLL. For simplicity, noise and polarization effects have been ignored in (1). We next assume that the EOM is driven by a single sinusoidal RF carrier with frequency $\omega_{\rm RF} = 2\pi f_{\rm RF}$. However, using the approach described below, the analysis can be extended to consider multiple carriers modulating the EOM. Assuming small optical-modulation depth and neglecting higher order harmonics, the total field E_0 at the output of the EOM can be simplified using Bessel functions to

$$\begin{aligned} E_0 = K \cdot \{J_0 - 2 \cdot J_1 \cdot \sin(\omega_{\rm RF} \cdot t)\} \\ \cdot \{\sin(\omega_0 + \omega_m)t + \sin(\omega_0 - \omega_m)t\} \end{aligned} \tag{2}$$

where K is a constant, $J_0 = J_0(\pi \cdot V/2 \cdot V_\pi)$ and $J_1 = J_1(\pi \cdot V/2 \cdot V_\pi)$ are Bessel functions, V is the peak amplitude of the applied RF voltage, and V_π is the half-wave voltage of the EOM.

The optical fiber can be modeled as a low-pass filter of negligible attenuation and a phase delay which depends on the optical frequency of the propagating signal [24]. The effect of fiber chromatic dispersion can then be taken into account by adding a constant phase delay to each component of the above optical field corresponding to the frequency of that component relative to ω_0. This phase delay ψ is given by [24]

$$\psi = -DL\lambda^2(\omega - \omega_0)^2/4\pi c \tag{3}$$

where D is the fiber dispersion parameter (ps/nm·km), L is the fiber length, λ is the operating wavelength, ω is the optical frequency of the mode, and c is the speed of light. The optical field after propagation through a fiber of length L then becomes

$$\begin{aligned} E' = K' \cdot [&J_1 \cdot \cos\{(\omega_0 + \omega_m + \omega_{\rm RF})t + \psi_3\} \\ &+ J_1 \cdot \cos\{(\omega_0 + \omega_m - \omega_{\rm RF})t + \psi_4\} \\ &+ J_1 \cdot \cos\{(\omega_0 - \omega_m + \omega_{\rm RF})t + \psi_5\} \\ &+ J_1 \cdot \cos\{(\omega_0 - \omega_m - \omega_{\rm RF})t + \psi_6\} \\ &- J_0 \cdot \sin\{(\omega_0 + \omega_m)t + \psi_1\} \\ &- J_0 \cdot \sin\{(\omega_0 - \omega_m)t + \psi_2\}] \end{aligned} \tag{4}$$

where E' is the output field, K' is a constant, and

$$\psi_1 = \psi_2 = -DL \cdot \lambda^2 \cdot (\omega_m)^2/4\pi c \tag{5a}$$
$$\psi_3 = \psi_6 = -DL \cdot \lambda^2 \cdot (\omega_m + \omega_{\rm RF})^2/4\pi c \tag{5b}$$
$$\psi_4 = \psi_5 = -DL \cdot \lambda^2 \cdot (\omega_m - \omega_{\rm RF})^2/4\pi c. \tag{5c}$$

After detection, the photodiode will produce a current which is proportional to $|E'|^2$, i.e., each mode in the optical spectrum will beat with all others to produce carrier components in the RF spectrum. Considering only those carrier components which are centered around the mm-wave frequency $(2\omega_m)$, and substituting (5a)–(5c) into the field expressions corresponding to the USB and the LSB, it can be shown that the amplitude of the detected carrier at $2\omega_m + \omega_{\rm RF}$, i.e., the USB will become zero after the fiber length $L_{\rm USB}$ given by

$$L_{\rm USB} = 4\pi^2 c/[D\lambda^2\omega_{\rm RF}(2\omega_m + \omega_{\rm RF})]. \tag{6}$$

Equation (6) is identical to that previously derived in [19] where a similar analysis was carried out for direct data modulation of a two-tone optical carrier. Similarly, the LSB at a frequency of $(2\omega_m - \omega_{\rm RF})$ will disappear at a fiber length given by

$$L_{\rm LSB} = 4\pi^2 c/[D\lambda^2\omega_{\rm RF}(2\omega_m - \omega_{\rm RF})]. \tag{7}$$

Taking $\lambda = 1.55$ μm, $D = 17$ ps/nm·km, $2f_m = 37$ GHz, and $f_{\rm RF} = 1.0$ GHz, we obtain from (6) and (7) the fiber lengths for which the RF power in the LSB and the USB will vanish as 204 and 193 km, respectively. If $f_{\rm RF} = 2.5$ GHz (the subcarrier frequency corresponding to the BPSK data), these lengths reduce to 85 and 74 km, respectively. These results clearly show that the HMLL can be used as a source of mm-wave optical carriers to distribute broad-band signals over fiber distances greater than 50 km between the central office and remote base-stations. In contrast, in direct detection mm-wave systems, fiber chromatic dispersion can limit the fiber distance to as short as 3 km when the operating frequency becomes 37 GHz or more [15]–[18]. While the attenuation of the mm-wave signal power is reduced in our system, it should be noted that the simple theory presented here does not take into account the effect of any decorrelation of the two optical carriers in the HMLL along the length of the fiber [18]. It has been shown that fiber chromatic dispersion also increases the phase noise of the detected mm-wave signal which can significantly limit the achievable transmission distance when higher order PSK modulation formats are implemented in mm-wave fiber-wireless systems [18].

IV. Conclusion

We have experimentally demonstrated a fiber-wireless system suitable for transport and distribution of broad-band signals. Using SCM techniques, three AM-VSB composite video channels and a 200-Mb/s digital data stream were simultaneously transmitted at 37 GHz over 10 km of single-mode fiber and successfully recovered in the receiver. Wireless distribution of these signals was also demonstrated using broad-band printed antennas. The weighted SNR of the recovered video channels was almost 40 dB and the data exhibited a BER of 10^{-9}. A simple analytical model was presented to characterize the effect of fiber chromatic dispersion on the transport of the mm-wave optical signals in our fiber-wireless system. Our analysis indicates that the optical carriers generated by an HMLL with repetition frequency of 37 GHz can be employed to successfully transport broad-band signals over fiber lengths greater than 50 km for subcarrier frequencies of less than 3 GHz. This distance can be increased to be greater than 150 km when subcarrier frequencies less than 1 GHz are employed.

REFERENCES

[1] H. Ogawa, D. Polifko, and S. Banba, "Millimeter-wave fiber optics systems for personal radio communications," *IEEE Trans. Microwave Theory Tech.*, vol. 40, pp. 2285–2293, Dec. 1992.

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

[3] J. B. Georges, D. M. Cutrer, O. Solgaard, and K. Y. Lau, "Optical transmission of narrowband millimeter-wave signals," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 2229–2240, Sept. 1995.

[4] D. Novak, Z. Ahmed, R. B. Waterhouse, and R. S. Tucker, "Signal generation using pulsed semiconductor lasers for application in millimeter-wave wireless links," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 2257–2262, Sept. 1995.

[5] 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, 1994.

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

[7] J. 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.

[8] D. Wake, C. R. Lima, and P. R. Davies, "Optical generation of millimeter-wave signals for fiber-radio systems using a dual mode DFB semiconductor laser," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 2270–2276, Sept. 1995.

[9] J. Park and K. Y. Lau, "Millimeter-wave (39 GHz) fiber-wireless transmission of broadband multichannel compressed digital video," *Electron. Lett.*, vol. 32, pp. 474–476, 1996.

[10] J. F. Cadiou, F. Devaux, J. F. Veillard, B. L. Marty, J. Guena, E. Penard, and P. Legaud, "Electroabsorption modulator for radio over fiber at 38 GHz," *Electron. Lett.*, vol. 31, pp. 1273–1274, 1996.

[11] C. H. Von Helmolt, U. Krug, K. Kruger, and L. Kuller, "58 GHz fiber optic upconverter applicable to wireless communication systems," in *Proc. OFC'96*, San Jose, CA, Feb. 1996, pp. 209–210.

[12] Z. Ahmed, D. Novak, H. F. Liu, and R. B. Waterhouse, "Optically-fed millimeter-wave (37 GHz) transmission system incorporating a hybrid mode-locked semiconductor laser," *Electron. Lett.*, vol. 32, pp. 1790–1792, 1996.

[13] D. Mathoorasing, S. Bouchoule, C. Kazmierski, E. Pernard, Ph. Dueme, A. Dravet, P. Nicole, M. Scheller, J. R. Bois, C. Rumelhard, Zahzouh and C. Devaux, "Wideband optoelectronic mixer for radio over fiber applications at 28/38/60 GHz," *Electron. Lett.*, vol. 32, pp. 1900–1901, 1996.

[14] L. Noel, D. Marcenac, and D. Wake, "120 Mb/s QPSK radio-fiber transmission over 100 km of standard fiber at 60 GHz using a master/slave injection locked DFB laser source," *Electron. Lett.*, vol. 32, pp. 1895–1897, 1996.

[15] H. Schmuck, "Comparison of optical millimeter-wave system concepts with regard to chromatic dispersion," *Electron. Lett.*, vol. 31, pp. 1848–1849, 1995.

[16] R. Hofstetter, H. Schmuck, and R. Heidemann, "Dispersion effects in optical millimeter-wave systems using self-heterodyne method for transport and generation," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 2263–2276, Sept. 1995.

[17] G. H. Smith, D. Novak, and Z. Ahmed, "Optimization of link distance in fiber-radio systems incorporating external modulators," in *Proc. Aust. Conf. Opt. Fiber Technol.*, Gold Coast, Australia, Dec. 1996, pp. 141–144.

[18] U. Gliese, S. Norskov, and T. N. Nielsen, "Chromatic dispersion in fiber-optic microwave and millimeter-wave links," *IEEE Trans. Microwave Theory Tech.*, vol. 44, pp. 1716–1724, Oct. 1996.

[19] R. A. Griffin, P. M. Lane, and J. J. O'Reilly, "Dispersion-tolerant subcarrier data modulation of optical millimeter-wave signals," *Electron. Lett.*, vol. 32, pp. 2258–2260, Nov. 1996.

[20] Z. Ahmed, H. F. Liu, D. Novak, Y. Ogawa, M. D. Pelusi, and D. Y. Kim, "Locking characteristics of a passively mode-locked monolithic DBR laser stabilized by optical injection," *IEEE Photon. Technol. Lett.*, vol. 8, pp. 37–40, Jan. 1996.

[21] R. Olshansky, V. A Lanzisera, S. F. Su, R. Gross, A. M. Forcucci, and A. H. Oakes, "Subcarrier multiplexed broad-band service network: A flexible platform for broad-band subscriber services," *J. Lightwave Technol.*, vol. 11, pp. 60–68, Jan. 1993.

[22] G. Huston, P. Shepard, and J. Brice, *Color Television System Principles Engineering Practice Applied Technology*. New York: McGraw-Hill, 1990.

[23] G. J. Meslener, "Chromatic dispersion induced distortion of modulated monochromatic light employing direct detection," *IEEE J. Quantum Electron.*, vol. 20, pp. 1208–1216, Oct. 1984.

[24] A. F. Elrefaie, R. E. Wagner, D. A. Atlas, and D. G. Daut, "Chromatic dispersion limitations in coherent lightwave transmission system," *J. Lightwave Technol.*, vol. 6, pp. 704–709, May 1988.

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