Generation and Transmission of FM and $\pi/4$ DQPSK Signals at Microwave Frequencies Using Harmonic Generation and Optoelectronic Mixing in Mach–Zehnder Modulators

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Abstract— **A novel method of using the harmonic generation and optoelectronic mixing properties of Mach–Zehnder modulators to generate modulated subcarrier signals at high-order harmonics of the input signals is presented. The method permits the simultaneous transmission over optical fiber of a modulated and an unmodulated signal, both at high-order harmonic frequencies of the input signals, for the purpose of transmitting both a local oscillator tone and the modulated signal required at a base station for microcellular applications. We present the theory of operation and demonstrate the validity of the concept with a narrow band single-tone FM experiment as well as a 20-Mb/s $\pi/4$ DQPSK experiment.**

I. Introduction

DEMAND for wireless cellular communications is escalating rapidly worldwide. One of the most attractive features of the cellular system is the provision for the users to reach anyone within the service area at any time. The widely used cellular telephone enables this mobility by allowing the user to be connected to the public telephone network transparently as long as it is within the service area of the system. Cellular division of the total coverage area opens up the possibility of frequency re-use in the system, that is, the same channel frequencies assigned to a particular cell can be re-used at a distant cell where interference between the two cells is minimal due to signal attenuation. It has been documented that the microcellular system, which contains smaller cells (microcells), promises effective frequency utilization and is believed to have the greatest potential in satisfying the increasing demand for mobile communications [1].

Two major problems arise when considering the design of a microcellular system. First, as the average distance between microcells shrinks, the risk of interference between distant cells increases. This can be remedied by operating the system in the microwave or millimeter-wave frequency range. RF signals at such high frequencies are absorbed readily by oxygen and water molecules and are further attenuated by rainfall; this property can be exploited to limit the practical radiation range of a base station thus alleviating the risk of interference. If an in-building cellular system is contemplated for broadband LAN applications, the interior walls of the building also offer additional isolation between cells. In addition, the relative bandwidth available in this frequency range is also higher and thus more channels can be allocated [2]. The second problem is that a large number of base stations are required in order to cover a given area. For example, it has been estimated that 5000 base stations would be required to service the Tokyo metropolitan area [3]. Therefore, it is vital to develop compact and simple base stations in order for the microcellular system to become economically viable. A possible solution is to relocate all the modulators/demodulators and system control circuitry away from the base stations to a central office. The base stations must then be connected to the central office via a feeder network which carries the calls (in the form of microwave or millimeter wave signals) to and from the base stations. Advances in optical fiber technology, particularly in the use of subcarrier multiplexed transmission for CATV applications [4], [5] and for communicating between satellite receivers and other land-based equipment [6], make the application of subcarrier multiplexed transmission over fiber attractive for the transmission of signals from a central office to a base station [7].

UHF mobile radio systems using an optical fiber feeder have been analyzed and demonstrated [8]–[10]. However, since microwave and millimeter-wave frequencies are more suitable to microcellular applications, and since most commercially available optical sources do not have modulation bandwidths that extend into the 20-GHz region, much less to 50–60 GHz, which is a proposed frequency band for future use in cellular applications, various techniques for generating optical signals at frequencies beyond the bandwidths of available optical sources have been proposed and studied. Some of these novel techniques include electrical heterodyne and photodiode mixing [11], optical heterodyne [12], laser nonlinearity [13] and indirect optical injection-locking [14], frequency modulation to intensity modulation conversion [15], feed forward optical modulation [16], and external modulator nonlinearity [17].

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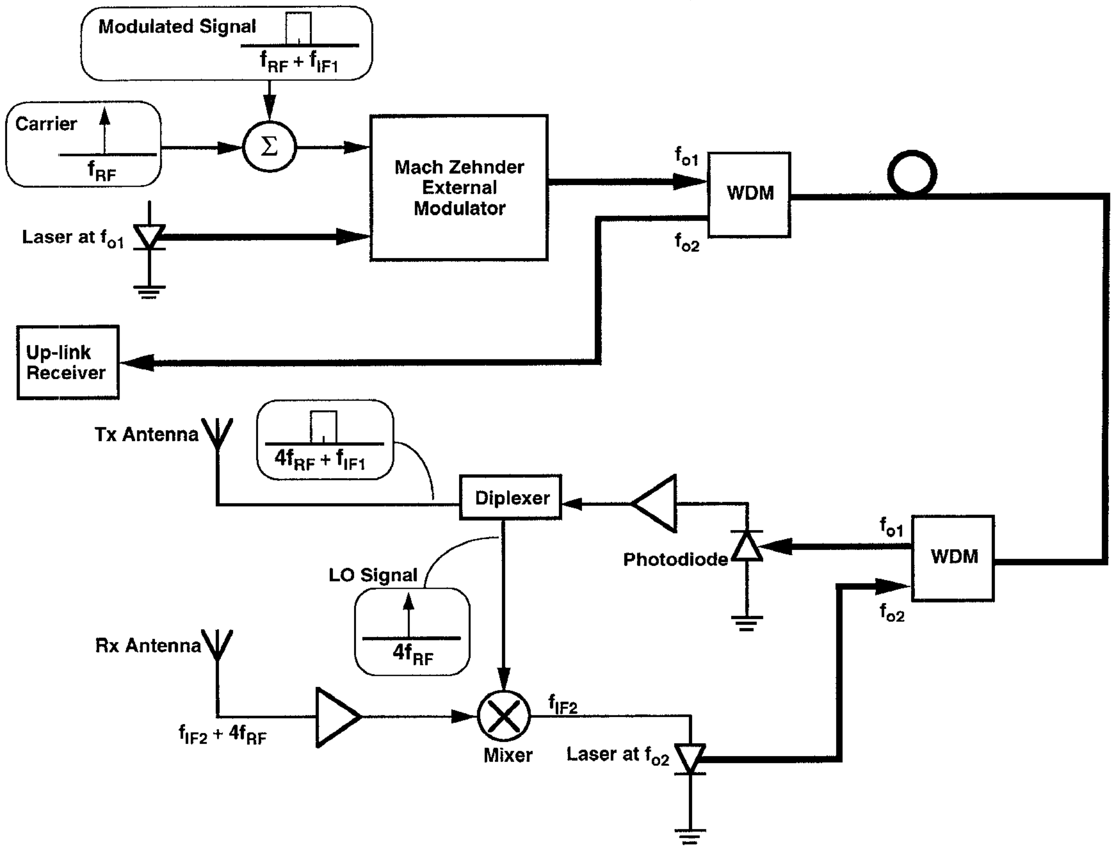

Fig 1. System block diagram.

In this paper, we present a novel technique which utilizes the harmonic generation and optoelectronic mixing properties of the Mach–Zehnder modulator to up convert the modulating signal applied to the modulator. In addition, we present a system level description in which not just the modulated signal is frequency translated upward, but we show that the addition of an unmodulated tone at the central office transmitter can also be effectively used to transmit and generate a high-order harmonic for use as a local oscillator tone at the base station; this local oscillator tone serves the purpose of down converting the received signal prior to transmission at an intermediate subcarrier frequency that inexpensive lasers can handle. In Section II, this technique is introduced in the context of a microcellular system. The theory behind the proposed technique is described in Section III and verified in Section IV with experimental data in which we transmit and receive, over fiber, a frequency-modulated signal near the fourth harmonic of the modulating signal. Finally, Section V contains a preliminary $\pi/4$ DQPSK experiment at 20 Mb/s to demonstrate the broadband capability of the system.

II. Mach–Zehnder Modulator as a Frequency Up-Converter in a Microcellular System

If optical fiber is employed in the feeder portion (central office to base station) of a microcellular system operating at microwave or millimeter-wave frequencies, it would be desirable that the optical carrier also be modulated at these high frequencies. For example, it has been shown in [18] and [19] that the inherent nonlinearity of a Mach–Zehnder modulator, when biased at its quadrature point, can be utilized to extend the bandwidth of the modulator so that a significant amount of power is detected at its second or fourth harmonic. From a microcellular system perspective, in addition to the up-conversion of the information signal, it is also desirable to transmit an unmodulated carrier alongside the information signal down the fiber. In this paper we present a novel technique that combines the harmonic generation property and the optoelectric mixing [20] characteristic of the Mach–Zehnder modulator, which can generate both the up converted information signal as well as the unmodulated carrier at the even harmonics.

Fig. 1 demonstrates how both the modulated and unmodulated carriers can be used in a microcellular system. Note that this block diagram is similar to the one proposed in [19] but is significantly simpler in that only one external modulator and no narrow band optical filters at the laser frequency and its signal sidebands are required. Hence, optical hardware requirements are significantly reduced. From the block diagram of Fig. 1, we see that by using wavelength division multiplexers (WDM), bi-directional transmission is possible with the use of two lasers at different wavelengths. One optical carrier at optical frequency f_{o1} (for example, at 1300 nm) carries the signal from the central office to the base station, the other carrier, at optical frequency f_{o2} (for example, at 1550 nm) carries the signal in the reverse direction. Alternatively, the WDM couplers could be replaced by optical circulators in which case lasers at any frequency could be used.

As will be explained in the following section, the nonlinear transfer characteristic of the Mach–Zehnder modulator can be used to generate both an unmodulated carrier as well as the information signal at frequencies near the even harmonics of the original input signals. At the base station, the diplexer then filters out the information signal at the desired frequency, which in our experiments we choose to be at $4f_{\rm RF}+f_{\rm IF1}$. This signal is then radiated through the antenna and received by the portable phone user. The other output of the diplexer permits the unmodulated carrier at $4f_{\rm RF}$ to pass to the local oscillator port of the electrical mixer, thereby providing remote control of the base station transmitter and receiver frequencies by the central office. The return signal transmitted by the portable phone is now down converted to $f_{\rm IF2}$ by the mixer. Since the return signal does not have to be radiated at microwave or millimeter-wave frequencies at the central office, $f_{\rm IF2}$ can be chosen to fall within the bandwidth of the laser diode at f_{o2} and the laser can be directly modulated in the up link direction. Using this technique the base station can be constructed with minimal and low cost hardware.

III. Mach–Zehnder Modulator as a Harmonic Generator and Opto-Electric Mixer

Generally, the nonlinearity of any device can be exploited to perform mixing and harmonic generation functions to some extent. The Mach–Zehnder modulator, which has a nonlinear transfer characteristic, can also be used as a harmonic generator and an optoelectric mixer simultaneously. More specifically, the optical output power of a Mach–Zehnder modulator is given by

$$P_{\rm opt}(t)=\frac{T\cdot P_{\rm in}}{2}\left[1+\cos\left[\frac{\pi V(t)}{V_\pi}\right]\right] \tag{1}$$

where V_π is the modulator switching voltage, $P_{\rm in}$ is the optical power level at the input of the modulator, and T is the fractional insertion loss of the modulator. $V(t)$ is the total voltage applied to the modulator including both the dc bias and the modulating signal. After transmission through some length of fiber, the detector photocurrent can be given as

$$I_{\rm out}(t)=\frac{T\cdot L\cdot P_{\rm in}\cdot\Re}{2}\left[1+\cos\left[\frac{\pi V(t)}{V_\pi}\right]\right] \tag{2}$$

where $\Re$ is the responsivity of the photodiode (in A/W) and L is the net optical loss from the output of the modulator to the photodiode.

In order to utilize the modulator as a mixer, we must feed in at least two signals at different frequencies. We let these be an unmodulated signal at frequency $f_{\rm RF}$ and a phase or frequency modulated signal at carrier frequency $f_{\rm RF}+f_{\rm IF1}$. Thus we can write for the total input signal

$$\begin{aligned}V(t)=V_\pi(1-\varepsilon)+\alpha V_\pi\cos[2\pi(f_{\rm RF}+f_{\rm IF1})t+m(t)]\\ +\beta V_\pi\cos(2\pi f_{\rm RF}t).\end{aligned} \tag{3}$$

The first term in (3) is the dc bias voltage, which sets the operating point of the Mach–Zehnder modulator; for example, if $\varepsilon=0,\pm1,\pm2,\ldots$ etc., the modulator is biased at quadrature. The second term is the phase- (or frequency-) modulated signal at the frequency $f_{\rm RF}+f_{\rm IF1}$ with its amplitude defined by the constant α normalized to V_π. $m(t)$ is the phase- (or frequency-) modulating base band signal that is to be recovered in the final output. The third term is an unmodulated carrier at the frequency $f_{\rm RF}$ with its amplitude defined by β, which is also normalized to V_π. Substituting (3) into (2), setting $\varepsilon=0$ (i.e., the modulator is biased at quadrature) and carrying out the expansion yields

$$I_{\rm out}(t)=\frac{T\cdot L\cdot P_{\rm in}\cdot\Re}{2}\times\begin{bmatrix}1+\sin[\pi\alpha\cos(2\pi(f_{\rm RF}+f_{\rm IF1})t+m(t))]\\ \quad\times\sin[\pi\beta\cos(2\pi f_{\rm RF}t)]\\ -\cos[\pi\alpha\cos(2\pi(f_{\rm RF}+f_{\rm IF1})t+m(t))]\\ \quad\times\cos[\pi\beta\cos(2\pi f_{\rm RF}t)]\end{bmatrix}. \tag{4}$$

Now, identities involving Bessel functions can be used to expand each of the composite trigonometric functions in (4) into an infinite sum of cosines. These identities are [21]

$$\begin{aligned}\cos[x\cos(y)]&=J_0(x)-2J_2(x)\cos(2y)\\&\quad+2J_4(x)\cos(4y)-\cdots\\ \sin[x\cos(y)]&=2J_1(x)\cos(y)-2J_3(x)\cos(3y)\\&\quad+2J_5(x)\cos(5y)-\cdots.\end{aligned} \tag{5}$$

The result is that each of the two products within the large square brackets in (4) represent a multiplying or mixing process involving two infinite sums. One of the sums contains harmonics of the modulated information signal while the other contains harmonics of the unmodulated carrier. In other words, the harmonics of the unmodulated carriers are used to up-convert each of the modulated information signal harmonics. This can be verified by carrying out the expansion, yielding

$$I_{\rm out}(t)=\frac{T\cdot L\cdot P_{\rm in}\cdot\Re}{2}\times\begin{bmatrix}1-J_0(\pi\alpha)J_0(\pi\beta)\\ +2J_1(\pi\alpha)J_1(\pi\beta)\cos[2\pi(f_{\rm IF1})t+m(t)]\\ -2J_2(\pi\alpha)J_2(\pi\beta)\cos[2\pi(2f_{\rm IF1})t+2m(t)]\\ +2J_3(\pi\alpha)J_3(\pi\beta)\cos[2\pi(3f_{\rm IF1})t+3m(t)]\\ +\cdots\\ +2J_0(\pi\alpha)J_2(\pi\beta)\cos[2\pi(2f_{\rm RF})t]\\ +2J_1(\pi\alpha)J_1(\pi\beta)\cos[2\pi(2f_{\rm RF}+f_{\rm IF1})t+m(t)]\\ -2J_1(\pi\alpha)J_3(\pi\beta)\cos[2\pi(2f_{\rm RF}-f_{\rm IF1})t-m(t)]\\ +2J_2(\pi\alpha)J_0(\pi\beta)\cos[2\pi(2f_{\rm RF}+2f_{\rm IF1})t+2m(t)]\\ +2J_2(\pi\alpha)J_4(\pi\beta)\cos[2\pi(2f_{\rm RF}-2f_{\rm IF1})t-2m(t)]\\ -2J_3(\pi\alpha)J_1(\pi\beta)\cos[2\pi(2f_{\rm RF}+3f_{\rm IF1})t+3m(t)]\\ -2J_3(\pi\alpha)J_5(\pi\beta)\cos[2\pi(2f_{\rm RF}-3f_{\rm IF1})t-3m(t)]\\ +\cdots\\ -2J_0(\pi\alpha)J_4(\pi\beta)\cos[2\pi(4f_{\rm RF})t]\\ -2J_1(\pi\alpha)J_3(\pi\beta)\cos[2\pi(4f_{\rm RF}+f_{\rm IF1})t+m(t)]\\ +2J_1(\pi\alpha)J_5(\pi\beta)\cos[2\pi(4f_{\rm RF}-f_{\rm IF1})t-m(t)]\\ -2J_2(\pi\alpha)J_2(\pi\beta)\cos[2\pi(4f_{\rm RF}+2f_{\rm IF1})t+2m(t)]\\ -2J_2(\pi\alpha)J_6(\pi\beta)\cos[2\pi(4f_{\rm RF}-2f_{\rm IF1})t-2m(t)]\\ -2J_3(\pi\alpha)J_1(\pi\beta)\cos[2\pi(4f_{\rm RF}+3f_{\rm IF1})t+3m(t)]\\ +2J_3(\pi\alpha)J_7(\pi\beta)\cos[2\pi(4f_{\rm RF}-3f_{\rm IF1})t-3m(t)]\\ +\cdots\end{bmatrix}. \tag{6}$$

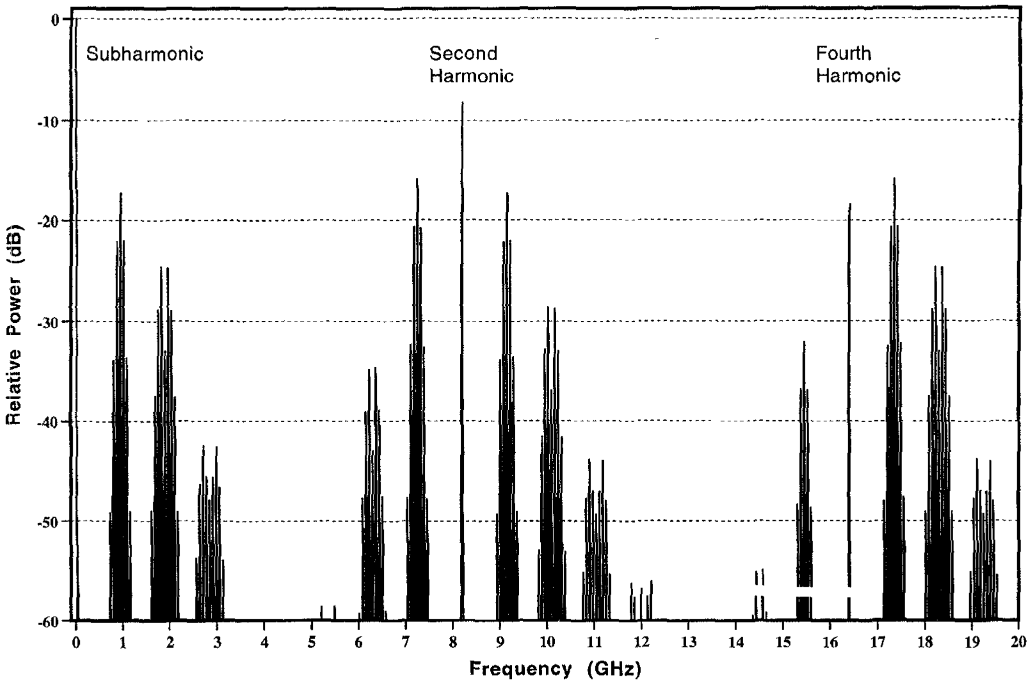

Fig. 2. Simulated spectrum for the proposed technique.

Note that unmodulated carriers are indeed present at even multiples of $f_{\rm RF}$; only even harmonics are present because the dc bias point was chosen to be V_π, which leads to the suppression of all odd harmonics. In addition, (6) shows that the information signals are offset from the even harmonics of the unmodulated carrier at harmonic intervals of $f_{\rm IF}$. This allows for an extra degree of flexibility in increasing the transmission frequency of the system. Since $m(t)$ is simply multiplied by a constant in each of the information terms after the up-conversion, (6) also suggests that it is possible to send any kind of phase- (or frequency-) modulated signal at frequencies of $2f_{\rm RF} \pm nf_{\rm IF}$, $4f_{\rm RF} \pm nf_{\rm IF}$, etc. One of the properties inherent in this modulation technique is that the transmission bandwidth of the information signal increases linearly with the harmonic order n since the phase- or frequency-modulation index (the constant in front of $m(t)$) is multiplied by n as shown in (6). A physical limitation to this technique is the decreasing signal amplitude achievable for higher harmonics or larger n. This is a result of the fact that the effective amplitude modulation index for a particular carrier is given by the combination of Bessel function terms in (6). By choosing their arguments appropriately, the power levels at the desired frequencies can be optimized. Furthermore, by selecting $f_{RF} + f_{IF}$ to be near the upper limit of the frequency response of the Mach–Zehnder modulator, a linearly modulated (frequency or phase modulated) signal at $nf_{IF} +$ (2 or 4) f_{RF} with significant output power can be obtained. Had we chosen to amplitude modulate the signal at f_{IF} it would appear as a modulation superimposed on the amplitude coefficient αV_π in (3), which in turn would appear in the optical output embedded in the arguments of the appropriate Bessel functions, and hence, would be significantly distorted. Furthermore, angle modulation formats have significant signal to noise ratio advantages over amplitude modulation. For these reasons, and compatibility with existing and emerging UHF cellular formats, two forms of angle modulation are used in the experimental section of this paper.

Fig. 2 is a simulated electrical spectrum based on (1). $f_{\rm IF1}$ and $f_{\rm RF}$ used in the simulation are 0.95 and 4.1 GHz, respectively, and the modulation format employed is FM. As predicted by (6), there are indeed unmodulated carriers at the even harmonics of 8.2 and 16.4 GHz. Note also the presence of frequency modulated information signals offset from the unmodulated carriers at intervals of 0.95 GHz. Finally, observe that the FM information signal bandwidths increase as they move further away from the unmodulated carriers at 8.2 and 16.4 GHz, which is also in agreement with (6).

IV. FM Experiments

Frequency modulation is used in this section to verify the integrity of the modulating signal using the proposed modulation technique. FM is chosen because it can be easily generated using a conventional signal generator and its spectrum can be readily verified using a spectrum analyzer and compared with the simulated spectrum.

While one of the eventual applications of this up-conversion technique is for wireless networks operating in either the 20 or 50–60 GHz regions, our current experimental capabilities limit implementation to input frequencies up to around 5 GHz. The experiments presented are intended to demonstrate the correctness of the theory and the viability of the proposed up-conversion concepts. To this end, Fig. 3 shows the block diagram of the hardware configuration for this experiment where we focus on the use of frequencies near the fourth harmonic at 16.4 GHz of the unmodulated carrier at $f_{\rm RF}$, which is chosen to be 4.1 GHz. To generate a modulated

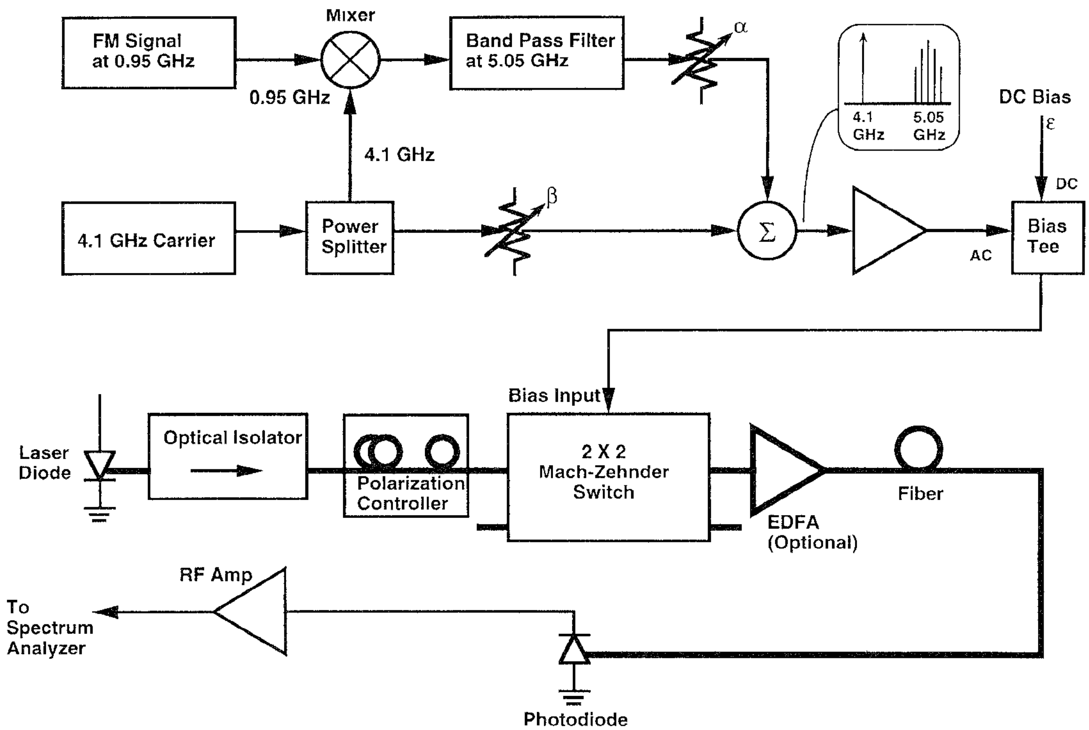

Fig. 3. Hardware setup for FM experiments.

signal we frequency modulate a carrier at 0.95 GHz with a 50-kHz tone, with a frequency modulation index of 1, giving a frequency deviation of 50 kHz. With f_{IF1} set to 0.95 GHz, the first information signal up-converted to appear above the fourth harmonic of f_{RF} will be at 17.35 GHz ($4f_{RF} + f_{IF1}$). In order to generate $V(t)$ as defined by (3), a microwave mixer is used to up-convert the FM signal to $f_{RF} + f_{IF1}$ (5.05 GHz). The up-converted FM signal is then combined with the unmodulated carrier at 4.10 GHz and the composite signal is amplified and fed to the AC input of the bias tee. Attenuators are used to adjust the amplitude constants α and β independently so as to maximize the power in the desired harmonic in the final output. DC bias is added at the bias tee to set the operating point of the Mach–Zehnder modulator at quadrature so that only even harmonics of f_{RF} are present. The signal at the output of the bias tee constitutes $V(t)$ as defined in (3), which is then fed to the Mach–Zehnder switch as the modulating voltage.

On the optical side, a 1551-nm DFB laser with a maximum output of +6.0 dBm is used. The optical isolator reduces back reflections into the laser. A polarization controller is also employed to adjust the polarization of light entering the Mach–Zehnder modulator to optimize its performance. This input power to the Mach–Zehnder is +3.2 dBm and the maximum output power of the modulator is −6.6 dBm, giving the insertion loss of 9.8 dBm. The 3-dB bandwidth of the Mach–Zehnder switch is ~7–8 GHz, and our experiment is designed to show that the amplitudes of the harmonic signals are unaffected by the modulator bandwidth, as long as the *input* signal frequencies are within the modulator bandwidth. The optical signal at the output of the Mach–Zehnder modulator is either detected immediately using a high speed p-i-n photodiode and then measured using a spectrum analyzer, or is amplified using an erbium-doped fiber amplifier (EDFA), transmitted through 20 km of signal mode fiber, detected by the p-i-n photodiode and electrically amplified before it is connected to the spectrum analyzer.

Without using the optical/electrical amplifiers and optical fiber, the detected electrical spectra at the output of the Mach–Zehnder modulator in the frequency range near $4f_{RF}$ are shown in Figs. 4 and 5. Fig. 4 is the unmodulated carrier at 16.40 GHz. It is important to observe that its line width is extremely narrow (~10 Hz) and is, within measurement capability, equal to that of the 4.1-GHz signal generator. This indicates that the phase noise of the laser, whose line width is >150 MHz, does not contribute to the broadening of the up-converted electrical carrier. This can be explained if we view this technique as an optical homodyne system where the optical local oscillator signal is generated, using the Mach–Zehnder nonlinearity, by the same source as the optical information carrier [17]. Hence, the phase noise of the two optical signals are highly correlated, which results in extremely narrow line width in a coherent optical system. Fig. 5 contains the FM spectrum of the information signal at 17.35 GHz. For comparison, the theoretical FM spectrum is shown in Fig. 6. By comparing Fig. 5 to Fig. 6, it is apparent that the relative amplitudes of the FM side bands are at the correct levels, hence, the FM spectrum is preserved using this technique.

To explore the transmission characteristics over fiber using this technique, an EDFA, 20 km of optical fiber, and an electrical amplifier were inserted into the system. The resulting information signal spectrum is depicted in Fig. 7. Even though 20 km of dispersive fiber and an EDFA were used, there is no

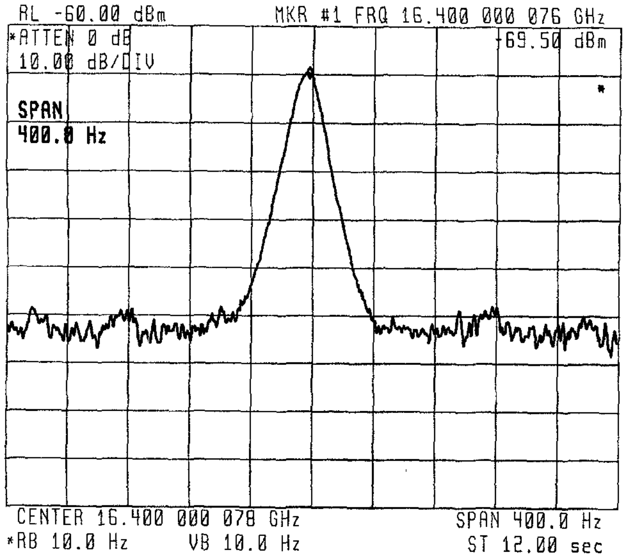

Fig. 4. Unmodulated carrier @ 16.40 GHz (no fiber/EDFA).

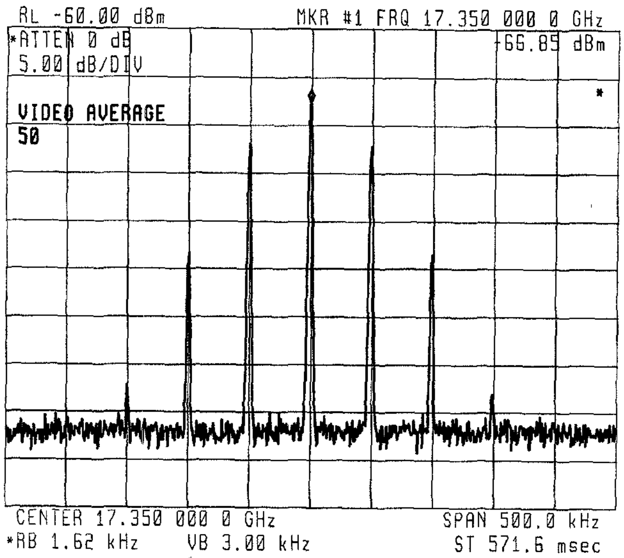

Fig. 5. FM signal @ 17.35 GHz (no fiber/EDFA).

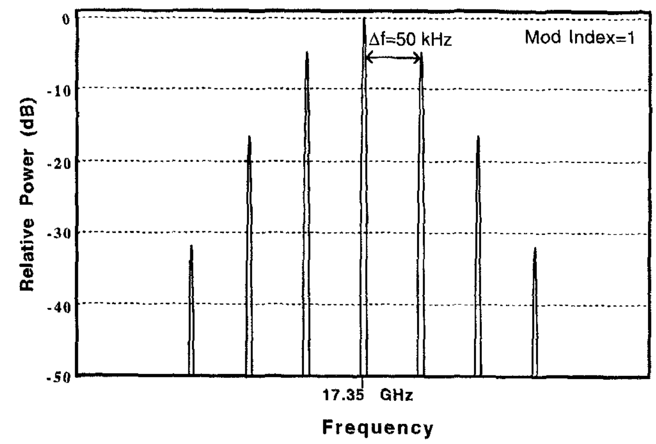

Fig. 6. Simulated FM spectrum @ 17.35 GHz.

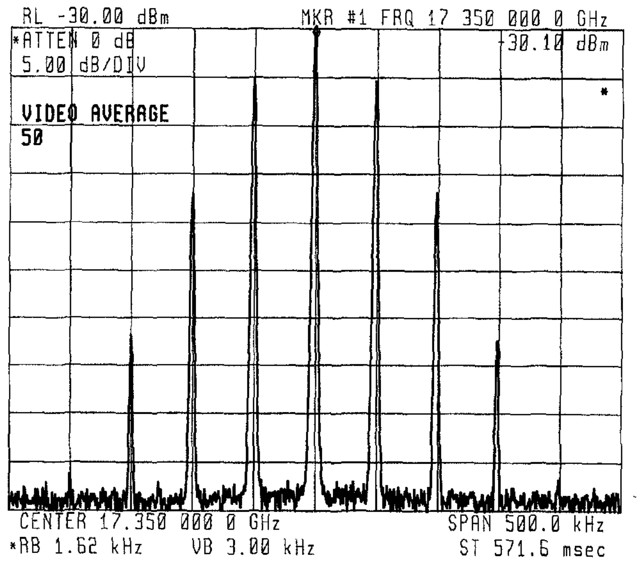

Fig. 7. FM signal @ 17.35 GHz (with fiber/EDFA).

observable degradation in the line width of the unmodulated carrier at 16.4 GHz and in the spectral shape of the detected FM signal at 17.35 GHz. In addition, with the use of an EDFA, there is approximately a 12 dB improvement in signal to noise ratio.

V. $\pi/4$ DQPSK Experiments

For this experiment, a 20-Mb/s $\pi/4$ DQPSK signal is used as a demonstration of the broadband capability of the proposed system. The $\pi/4$ DQPSK digital modulation format is chosen because it is the modulation scheme adopted by the North America Digital Cellular standard as well as the Personal Digital Cellular standard in Japan. Other phase or frequency modulation schemes that may be more suitable to a particular frequency range and channel characteristics can also be utilized, but this is beyond the scope of this paper.

For this experiment we replace the FM modulator and spectrum analyzer in Fig. 3 with the impulse response identification system (IRIS)[1] to generate and demodulate the $\pi/4$ DQPSK signals. Fig. 8 contains the demodulated constellation diagram at the output of the Mach–Zehnder modulator for 10 000 bits at the symbol rate of 10 Mega-symbols per second (or 20 Mb/s). The constellation is quite ideal and it can be expected that the bit-error-rate (BER) associated with such a signal would be minimal. Fig. 9 shows the constellation diagram of the same $\pi/4$ DQPSK signal when the optical amplifier and 20 km of fiber are inserted. Even though this constellation has degraded as compared to Fig. 8, accurate decision can still be made for each symbol. Quantification of the BER performance of $\pi/4$ DQPSK transmission over dispersive fiber in the presence of EDFA's is a topic for future research.

VI. Conclusion

A new method has been presented for the generation, modulation and transmission over optical fiber of microwave

[1]The IRIS system is a general purpose radio test set that allows modulation and demodulation of custom waveforms at UHF and microwave frequencies. It was developed by Bob Davies of AGT Limited.

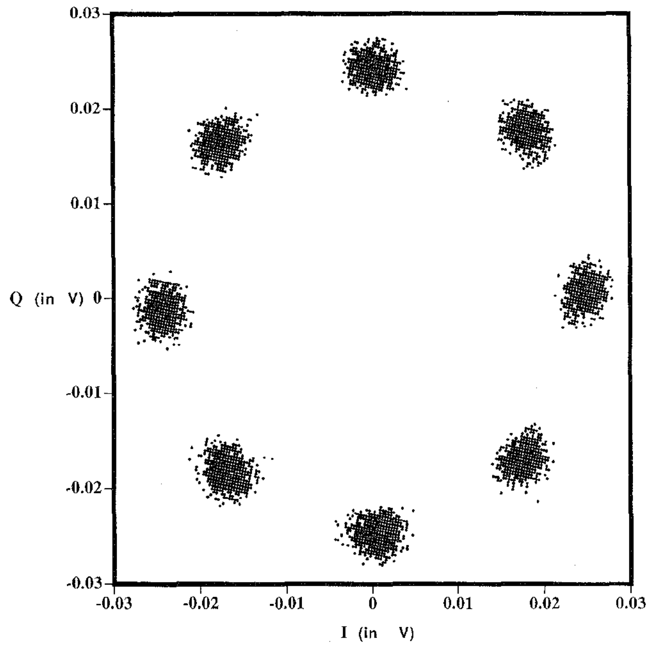

Fig. 8. $\pi/4$ DQPSK constellation at 20 Mb/s (@ the external modulator output).

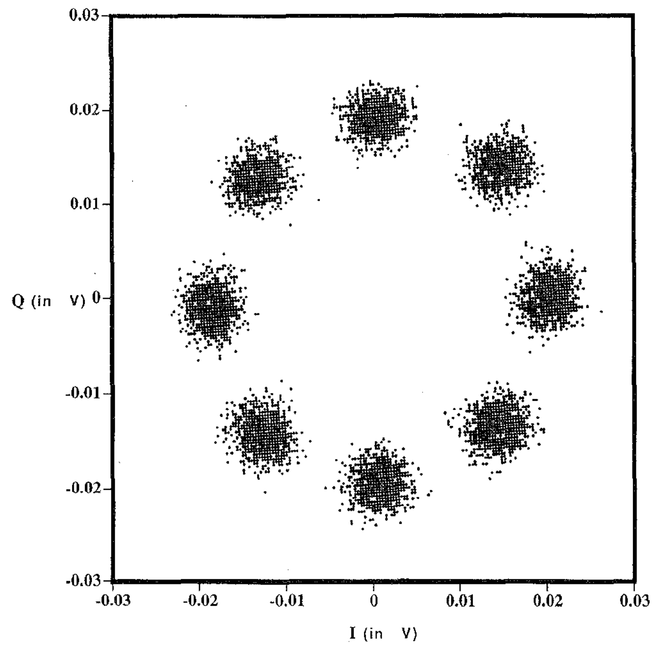

Fig. 9. $\pi/4$ DQPSK constellation at 20 Mb/s (after post Amp and 20 km of fiber).

signals. The method is based on the nonlinear mixing and harmonic generation associated with Mach–Zehnder modulators. We have demonstrated, for the first time, the transmission of single tone FM and 20 Mb/s $\pi/4$ DQPSK signals over fiber at distances up to 20 km with carrier frequencies in the 17–18 GHz region, using input signals less than 5.05 GHz.

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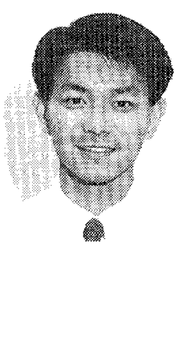

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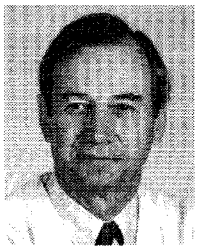

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