Indirect Subharmonic Optical Injection Locking of a Millimeter-Wave IMPATT Oscillator

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Abstract —**Large aperture phased-array antennas operating at millimeter-wave frequencies are designed for space-based communications and imaging. Array elements are composed of active transmit–receive (T/R) modules that are phase and frequency synchronized to a reference signal at the central processing unit by a fiber-optic (FO) distribution network. The implementation of FO links, synchronizing the millimeter-wave local oscillators (LO's), imposes a great challenge. This paper presents results of indirect optical injection locking of a free-running 38-GHz (*Ka*-band) IMPATT oscillator over the locking range of 2–132 MHz, depending on the injected power level (amplifier gain). In the experiment, the nonlinearity of both the laser diode and the IMPATT oscillator is exploited to achieve 12th subharmonic injection locking. The overall system FM noise degradation of the reference signal is 16 dB at 500-Hz offset. The FM noise degradation is dominated by the theoretical limit of 20log N, where N is the frequency multiplication factor used in subharmonic injection locking. Methods by which optical injection locking may be extended into 60 and 90 GHz are demonstrated.**

I. INTRODUCTION

FUTURE AIRBORNE phased-array antenna systems with as many as 10^4–10^5 solid-state transmit–receive (T/R) modules are designed for high-resolution and accuracy. To achieve a coherent detection, the T/R modules are synchronized to a master oscillator using injection-locking techniques. However, distribution of synchronizing signals to each element using the conventional coaxial feed networks is undesirable owing to their high loss, large size, and weight. Recent advances in MMIC processing facilitates low-cost integration of optoelectronic components with T/R modules; hence, distribution of control signals using lightweight fiber-optic (FO) links is an attractive alternative [1], [2]. One of the formidable challenges in optically controlled phased-array antennas is the frequency synchronization of the individual T/R modules, which requires FO synchronizing links operating at the millimeter-wave frequencies. This paper presents results of indirect optical injection locking of a free-running 38-GHz (*Ka*-band) IMPATT oscillator over the locking range of 2–132 MHz, as a function of the injected power level (amplifier gain). In this experiment, the nonlinearity of both the laser diode [3], [4] and the IMPATT diode is exploited to achieve a combined 12th subharmonic locking. Such an approach is essential because of the speed and sensitivity limitations of the optoelectronic components at millimeter-wave frequencies.

II. BACKGROUND

The concept of an optically controlled phased-array antenna, shown in Fig. 1, has been proposed and pursued by a number of researchers [1]–[9]. Phased-array antennas consist of three major subsystems: 1) the central processing unit (CPU); 2) the phased array with individual MMIC T/R modules; and 3) the distribution network. The antenna array is composed of independent (10000 or more), spatially distributed T/R modules fabricated on the basis of MMIC techniques. For such an antenna system, the distribution of data/control signals is achieved by the FO distribution network in place of the conventional coaxial or precision waveguide feeds. The FO network reduces the size and weight of the conventional feeds by at least a factor of 10 and provides larger bandwidth, immunity to interference (EMI and EMP), excellent crosstalk isolation, and lower transmission losses, particularly at the millimeter-wave frequencies. Operation in the optical domain facilitates novel optical signal processing schemes, such as true time delay phase-shifting for beam steering [10], [11].

The FO distribution network, connecting the CPU with the array, must provide for three functions. The first, and most important, relates to the synchronization of the array. The power radiated by the individual antennas will spatially combine only if the elements are phase synchronized. Furthermore, coherent detection requires frequency synchronization and time equalization of the active modules. The distribution of phase and frequency reference signals is a formidable task considering the number of T/R modules, and must be provided by the FO distribution network. The second function involves the distribution of control signals for beam forming and steering of the

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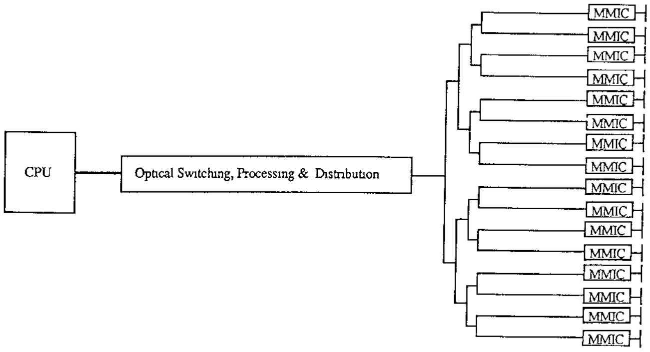


Fig. 1. Optically controlled phased array antenna concept.

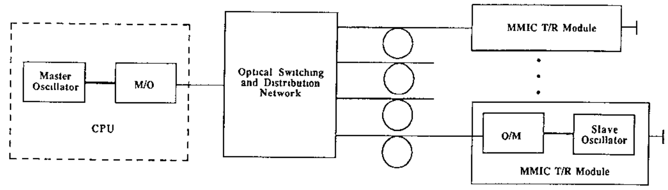


Fig. 2. Optical injection locking of the local oscillators in the T/R modules using the reference signal at CPU.

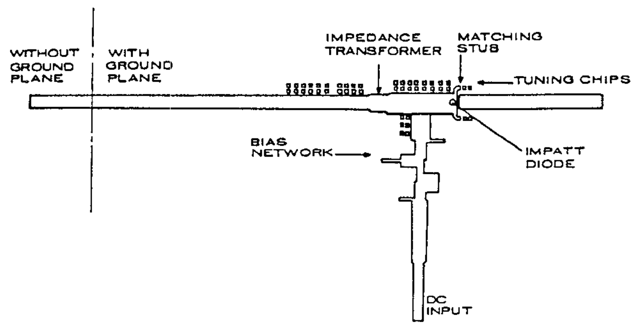


Fig. 3. Microstrip conductor pattern of the IMPATT oscillator

phased array. The third and final function of FO distribution is to transmit the communication/data. Clearly, some of these functions may be combined on the same link. It must be emphasized that the concept of the large-aperture phased array would functionally fail unless the frequency synchronization problem can be resolved. This is the problem addressed in this paper.

The frequency synchronization of local oscillators (LO's) is achieved at extremely high frequency (EHF) by injection locking. The EHF link (Fig. 2), which connects the master oscillator to the LO's, is the most difficult to implement. The main proponents of these links are the master oscillator, the modulation of the optical carrier at EHF, the distribution of the optical signal, and, finally, the detection of the optical signal to recover the frequency reference at the active T/R module.

The most critical elements of the EHF distribution system are the microwave-to-optical conversion (M/O), i.e., the modulator at the CPU level, and the optical-to-microwave conversion (O/M), or the demodulator. The microwave modulation of light can be accomplished either by the direct modulation of the semiconductor laser [12] or by external modulators using integrated optics [13]. The optical signal after distribution is coupled to the millimeter-wave active devices to achieve optical injection locking of the LO's. There are two approaches to optical injection locking of oscillators, namely, direct and indirect. Direct optical injection locking of IMPATT and FET oscillators up to X-band has been reported [5]–[8], but the coupling of light to the active region of the device has been very poor, resulting in an insignificant locking range. Indirect optical injection locking [9] means that the RF-modulated optical signal is first demodulated by a high-speed photodiode, amplified, and then electrically injected to the IMPATT or FET oscillator. This method has several advantages such as the efficient detection and subsequent amplification of the synchronizing signal prior to injection locking.

Future trends in millimeter-wave phased array antennas require FO synchronizing links in the frequency ranges of 20, 44, 60, and 94 GHz. However, room-temperature modulation bandwidths of electrooptic devices are presently limited to the microwave frequencies (X-band), and devices with bandwidths in excess of 30 GHz will not be available in the near future. Therefore, alternative techniques must be explored to overcome this gap and extend the bandwidth of the FO links to the millimeter-wave frequencies. One approach is to exploit the inherent nonlinearities of semiconductor laser diodes and millimeter-wave local oscillators, such as IMPATT and Gunn diodes, to generate harmonics, thereby extending the effective synchronizing link bandwidth. The goal of the present work is to demonstrate the feasibility of optical injection locking of oscillators at millimeter-wave frequencies.

III. IMPATT Oscillator Design and Fabrication

A millimeter-wave IMPATT oscillator was selected for the feasibility study. The IMPATT diode was fabricated from Si by established techniques that include controlled ion implantation, SIMS doping profile measurement, wafer thinning, and localized laser annealing [14]. The Ka-band free-running oscillator is designed and fabricated using planar millimeter-wave circuits compatible with monolithic and hybrid techniques. The microstrip oscillator circuit utilized in this experiment is shown in Fig. 3. The oscillator circuit consists of the IMPATT diode, a biasing, and impedance matching networks. A low-pass prototype Cauer filter is implemented in the bias network to minimize low-frequency instabilities. It consists of four open-circuit stubs separated by three quarter-wavelength transmission-line sections, and provides for higher cutoff frequency and adequate attenuation in the stopband of 23 GHz. The diode negative conductance and shunt capacitance are measured to be 0.025 mhos and 0.4 pf, respectively, where at 44 GHz the admittance of the diode is given by $Y_d = G_d + jB_d = -0.025 + j\ 0.111$ mhos. The device is matched with two 0.14-cm-long, 100-Ω stubs in parallel. Adjoining this diode is a quarter-wave transformer of 44.7 Ω, which is employed to transform the impedance to 50 Ω. In order to isolate the dc bias from the RF circuit, a microstrip dc block is used. Based on equiripple design, the even- and odd-mode impedances of the coupled lines are calculated as 188.7 Ω and 83.9 Ω, respectively.

The microstrip oscillator can be used in various applications. For example, it may be used as a unit cell that feeds an array of series-fed microstrip patch antennas in the transmit module. However, for the purposes of the present investigation, it is necessary to place the circuit in a waveguide below cutoff, to prevent propagation of unwanted waveguide modes. The waveguide enclosure does not require critical tolerances and is produced at a very low cost. The microstrip-to-waveguide transitions are necessary to permit measurements of the microstrip oscillator performance. The microstrip electric probe transition is used for ease of coupling. It consists of the microstrip line on the substrate, which is inserted in the *E*-plane of a rectangular *Q*-band waveguide. The optimum depth of penetration is adjusted based on the structural parameters of the microstrip line, substrate thickness, and dielectric constant. A maximum electric field at the location of the electric probe is attained by the use of a tunable short. This transition is capable of providing broad-band performance with low VSWR and low insertion loss. The IMPATT oscillator output power is a function of the driving current and was measured to be as high as 23 mW, with a 4-percent dc to RF conversion efficiency.

IV. Experimental Procedure

The experimental arrangement is shown in Fig. 4, depicting two free-running slave oscillators synchronized to a master oscillator through an FO link. For the optical source, a buried heterojunction (BH) AlGaAs injection laser, manufactured by Ortel Corporation, is used. The laser drive current, and hence the optical output, are directly modulated by a 3.235-GHz (f_o) signal from the master oscillator. The maximum laser optical output power is 10 mW at 830 nm and has a 3-dB small-signal bandwidth of 5 GHz for a driving current level corresponding to 80 percent of its maximum output power. The laser output is coupled to a multimode fiber (50/125 μm), with a 70-percent coupling efficiency. The laser diode's output is fused to a 3-dB optical coupler that splits the optical signal into two optical links.

In the first arm of the optical coupler, the modulated light is collimated using a 0.25-pitch selfoc lens, and then focused on a high-speed photodetector using a short-focal-length laser diode focusing lens from Melles Griot. The p-i-n photodetector is a GaAs p-i-n diode from Ortel Corporation that has a responsivity of 0.45 A/W at 840 nm with 10-dB bandwidth of 15 GHz at 20-V reverse-bias voltage. The fourth-harmonic signal $4f_o$ is generated by the laser diode under large-signal operation, and is amplified using two cascaded ac-coupled broad-band (6–18 GHz) amplifiers from Narda. The electrical signal could be tapped off after either the first or the second amplifiers, providing for gains of 22-dB and 45-dB, respectively. The

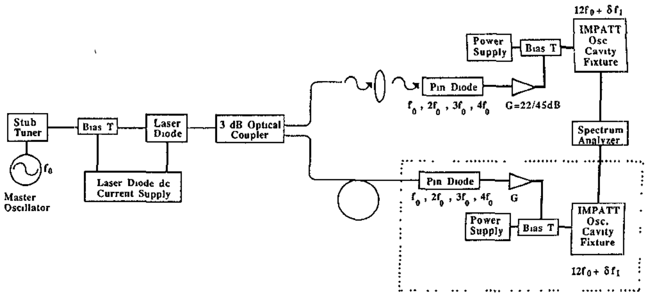


Fig. 4. Experimental setup for optical injection locking of two millimeter-wave IMPATT oscillators. The thick lines indicate signals in the electrical domain, whereas the thin lines represent the optical fibers. The wiggly arrows indicate the free-space optical focusing system. The dotted section is not presently used.

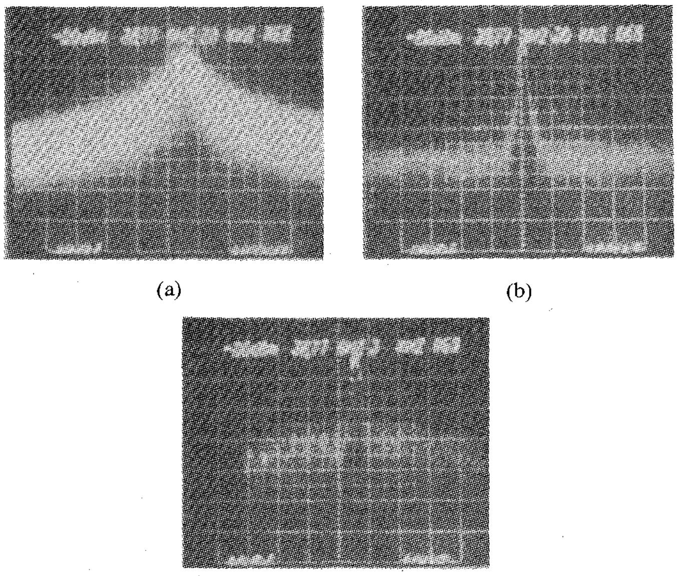
synchronizing signal is then electrically injected through a bias-tee to the biasing circuit of the free-running IMPATT oscillator circuit. The power spectrum of the IMPATT oscillator is observed on a spectrum analyzer using an external waveguide mixer.

The second arm of the optical coupler, which was not employed at the present experiment, can be used for the simultaneous injection locking of another IMPATT oscillator.

V. Experimental Results

The laser diode is intensity modulated at 3.235 GHz by an 8-dBm signal from a synthesized source (Systron Donner 1626). Under the large-signal driving condition, substantial harmonics are detected by the high-speed p-i-n photodetector [3], [4]. The detected signals, in particular the fourth-harmonic signal ($4f_o = 12.940$ GHz), measured to be as high as −55 dBm, is amplified by the LNA and is electrically injected into the free-running IMPATT oscillator, which is biased for output power in the range of several milliwatts. Injection locking is observed at three times the frequency of the injected electrical signal, or at $3 * 12.940$ GHz = 38.820 GHz. With respect to the master oscillator, the injection-locking process takes place at the 12th harmonic, i.e., $4 * 3 * f_o = 12 * 3.235$ GHz = 38.820 GHz. Even though the detected third harmonic of the master oscillator frequency at 9.705 GHz is higher in amplitude than the fourth harmonic at 12.940 GHz, the electrical injection at this frequency nevertheless does not contribute in the subharmonic injection-locking process. This is based on the results of subharmonic electrical injection locking at 9.705 GHz, corresponding to one-fourth of the IMPATT oscillation frequency, and was carried out prior to the indirect optical injection-locking experiment to characterize the oscillator's performance under forced oscillation. Furthermore, this performance predicts a third-order nonlinear oscillation behavior, which corresponds to the Van der Pol-type oscillator behavior [3]. Hence, the subharmonic injection locking is dominated by the 12.940-GHz rather than the 9.705-GHz control signal.

The power spectra of the free-running and injection-locked IMPATT oscillator are shown in Fig. 5. A significant improvement in the oscillator stability and FM noise level is observed. The single-sideband FM noise of the



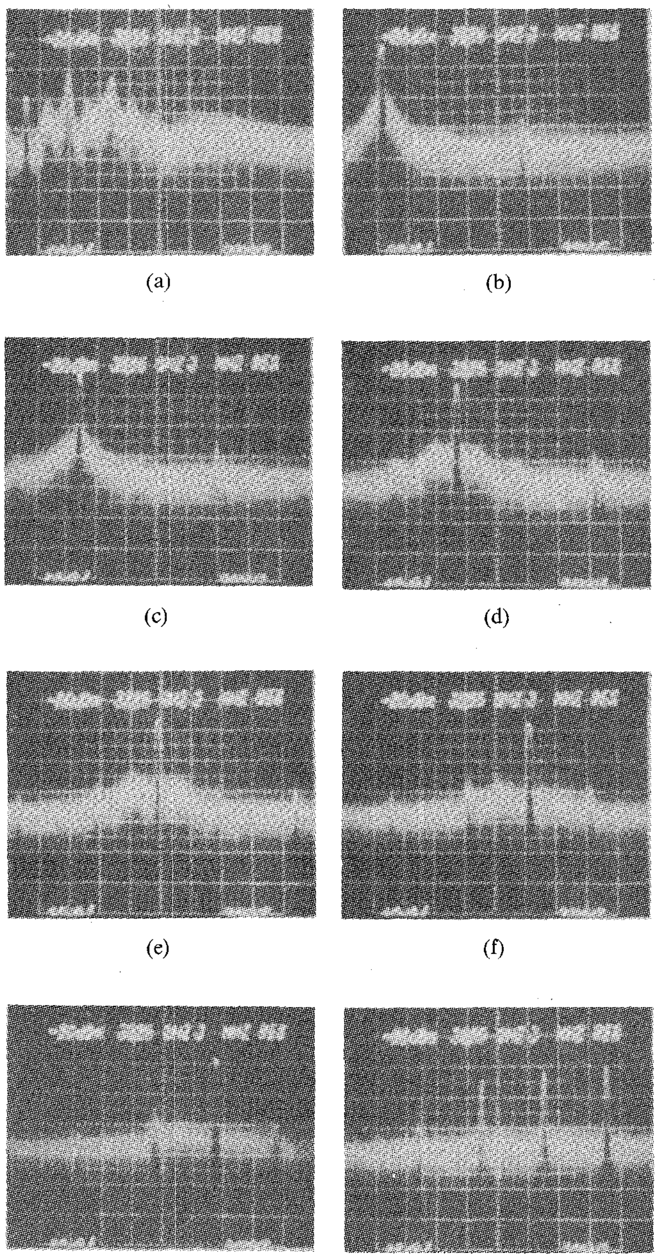
(a) (b) (c)

Fig. 5. Spectrum of the IMPATT oscillator before and after indirect optical injection locking by an S-band master source at 3.230 GHz (vertical scale is 10 dB/div). (a) Free-running at 38.77 GHz (horizontal scale is 100 kHz/div). (b) Injection-locked (horizontal scale is 100 kHz/div). (c) Injection-locked (horizontal scale is 10 kHz/div).

TABLE I
PHASE NOISE EVALUATION OF MASTER SOURCE IN THE OPTICAL LINK AND RESULTING SYSTEM PHASE NOISE DEGRADATION

Relative phase noise power level of:	500 Hz offset	5 KHz offset	500 Hz offset	5 KHz offset
Master oscillator (3.235GHz)	-58dBc/Hz	-79dBc/Hz	Reference	Reference
Detected master osc. signal (3.235GHz)	-56dBc/Hz	-77dBc/Hz	2dB	2dB
Detected 4th harmonic signal (12.940GHz)	-44dBc/Hz	-66dBc/Hz	12dB	11dB
Amplified fourth harmonic (12.940GHz)	-42dBc/Hz	-65dBc/Hz	2dB	1dB
Total system phase noise degradation			16dB	14dB

free-running IMPATT oscillator at 100-kHz offset carrier is measured to be ~ -50 dBc/Hz, which reduces drastically after injection locking. The FM noise of the injection-locked oscillator at 100-kHz offset is dominated by the measuring instrument (spectrum analyzer) noise, as is shown in Fig. 5(b). However, a close observation of the injection-locked IMPATT oscillator spectrum demonstrates FM noise level as low as -55 dBc/Hz at 5-kHz offset carrier, as shown in Fig. 5(c). The FM noise degradation of the synchronizing signal due to the FO link and amplifier stage is presented in Table I. The overall system FM noise degradation at 500-Hz offset is only 16 dB, where it is mainly dominated by the harmonic generation mechanism. This result corresponds with the theoretical expectation of $20 \log N$, where N is the harmonic number generated by large-signal modulation of the laser diode. The FO link FM noise contribution to the reference signal is only 2 dB, and the broad-band amplifier degrades it by another 2 dB.



(a) (b) (c) (d) (e) (f) (g) (h)

Fig. 6. Master–slave pulling range of IMPATT oscillator for eleven 1-MHz steps of master source. (a) 3.225 GHz (beginning of locking with sidebands). (b) 3.226 GHz (locked). (c) 3.228 GHz (locked). (d) 3.230 GHz (locked). (e) 3.232 GHz (locked). (f) 3.233 GHz (locked). (g) 3.235 GHz (locked). (h) 3.236 GHz (end of locking with sidebands). (Horizontal scale is 20 MHz/div and center frequency is 38.77 GHz.)

The locking range capability of the injection-locked oscillator is also investigated. A locking range in excess of 2 MHz is achieved with an amplifier gain of 22 dB. The injection-locking process for 45-dB amplification gain is depicted in Fig. 6, where a locking range in excess of 132 MHz is observed.

VI. DISCUSSION

The feasibility of the subharmonic indirect optical injection locking of a 38.9-GHz IMPATT oscillator using an S-band master source has been demonstrated. The millimeter-wave oscillator was synchronized to the 12th harmonic of the master oscillator using the nonlinear behavior of both the optical link and IMPATT diode. A locking range as high as 132 MHz was achieved using a 45-dB gain amplifier at 12 GHz. The FM noise degradation of the reference signal is measured to be only 16 dB, which resulted in an FM noise of -55dBc/Hz at 5-kHz offset for the injection-locked IMPATT oscillator.

The power budget, expressed in terms of the number of oscillators that can be locked to a single laser, is a key system consideration. Therefore, it is important to note that in the present arrangement only half of the available modulated optical power was utilized; thus, the simultaneous synchronization of two independent oscillators is attainable with the current setup. Further improvements in the FO link and in the microwave impedance matching between the optical detector and the LO should provide for simultaneous injection locking of additional oscillators. Optimization of the laser diode operating condition on the basis of the modulating frequency and modulation depth provides for larger harmonic content and should significantly increase the number of oscillators that can be synchronized by one laser.

The nonlinearities of the semiconductor injection laser and the IMPATT diode are exploited to use a combined 12th harmonic locking. One can extrapolate that with the availability of the larger bandwidth electrooptic components, indirect optical injection locking in the important frequency ranges of 60 and 90 GHz is becoming a distinct possibility. Other schemes, such as sideband injection locking, can be potentially employed to achieve larger pulling range at these frequencies of interest at the expense of greater complexity.

The prime source of the system FM noise degradation of the reference signal is the application of the fourth harmonic in the subharmonic injection locking. The theoretical limit is $20 \log N$, where N is the frequency multiplication factor generated by the large-signal modulation of the injection laser. However, the contribution from other FM noise sources such as optical link and the broad-band amplifier can be further minimized. The optical link noise degradation is dominated by the light scattering within the coherent length of the laser, which may be reduced by improving the FO link efficiency and an optical isolator at the laser output. The noise contribution of the amplifier may be minimized by replacing the broad-band amplifier by a narrow-band one that will reduce AM to PM conversion.

Indirect optical injection-locking technique is more desirable than the direct one. In particular, since the light coupling to the p-i-n photodiode is more efficient than the coupling to the active region of the IMPATT diode, a larger modulated power can be detected. Furthermore, amplification of the control signal prior to injection locking provides for a larger pulling range.

Further optimization of the system FM noise performance and efficiency and a theoretical power budget analysis of the IMPATT synchronizing link are presently being investigated to evaluate and demonstrate the feasibility of a hybrid optical/millimeter-wave transmit module.

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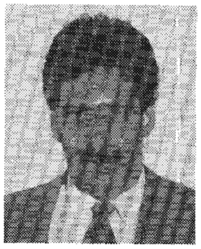
Dr. Herczfeld is a member of APS, SPIE, and the International Solar Society.



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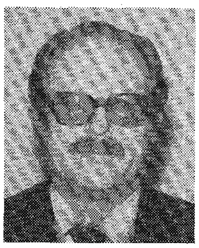
Dr. Daryoush has authored or coauthored over 30 technical publications in the area of light interaction with passive and active microwave devices, circuits, and systems. He has two U.S. patents pending in the area of optically controlled microwave circuits. He is a member of Sigma Xi.



Arye Rosen (M'77–SM'80) received the B.S.E.E. degree cum laude from Howard University in 1963 and the M.Sc.E. degree from the Johns Hopkins University, Baltimore, MD, which he attended on a Gillman Fellowship, in 1965. He received the M.Sc. degree in physiology from Jefferson Medical College, Philadelphia, PA.

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Dr. Sharma received the Best Paper Award in the Student Paper Contest organized by the IEEE India Section in 1975. He was awarded the IEEE Outstanding Student Member Award in 1975. He was Chairman of the MTT/ED Chapter of the IEEE Princeton Section during 1983/84. Since 1983, he has been Chairman of Membership Development for the IEEE Princeton Section.

V. M. Contarino, photograph and biography unavailable at the time of publication.