1.55-μm Photonic Systems for Microwave and Millimeter-Wave Measurement

Tadao Nagatsuma, *Member, IEEE*, Mitsuru Shinagawa, *Member, IEEE*, Nabil Sahri, Ai-ichiro Sasaki, Yakov Royter, and Akihiko Hirata

Invited Paper

***Abstract*—This paper reviews recent advances in 1.55-μm photonic systems for measurement and sensors covering the frequency range from microwaves to millimeter waves. We first deal with the basic technologies for photonic measurement, i.e., generation, transmission, and detection of high-frequency signals, and then discuss recent practical applications, including high-speed integrated-circuit probers, sampling oscilloscopes, network analyzers, and some free-space sensing systems.**

***Index Terms*—Electrooptic measurements, microwave/millimeter-wave measurements, optical pulse generation, optoelectronic devices, semiconductor lasers, time-domain measurements.**

I. Introduction

PHOTONIC technologies have recently been rapidly introduced to communications systems, where the combination of electronics and photonics offers higher performance, lower cost and greater functionality, and ease of use. The use of photonic techniques has also become essential to meet the ever-increasing demands, in terms of high-frequency measurement, placed on equipment for the testing and inspection of electronic components and systems.

For example, the operating frequencies of transistors have reached the terahertz range [1], and some integrated circuits (ICs) are now be able to operate at >100 GHz [2]. However, conventional techniques for measuring *electrical signals* suffer from insufficient bandwidth. The highest bandwidth for commercially available sampling oscilloscopes is 50 GHz (7-ps temporal resolution), and the equivalent for broad-band vector network analyzers is 110 GHz, which are capable of measurement with instantaneous wide-band frequency sweeps from a few tens of megahertz to millimeter-wave frequencies.

Against this background, novel measurement techniques based on all-electronic approaches have been proposed [3]–[6]. Nonlinear-transmission-line (NLTL) circuits are employed as signal generators, and Schottky-diodes are employed as sampling gates [3]. An electrical signal sampling circuit with a bandwidth of 725 GHz [4] and network analyzers that operate across the 7–200- [5] and 70–230-GHz [6] bands have been reported. Millimeter-wave monolithically integrated-circuit (MMIC) technology is the key to achieving the broad-band operation of these instruments. With an all-electronic approach, generating >300-GHz broad-band signals is a greater challenge than detecting such signals [7]. Waveguide-based and/or quasi-optical systems, however, offer higher frequency operation at up to 1 THz, although with a discontinuous bandwidth [8].

To overcome several technological limitations on all-electronic approaches, there has been increasing interest in, and expectations of, photonic techniques. The emergence of femtosecond and picosecond pulse lasers spawned a variety of photonic measurement techniques for high-frequency electronics in the 1980's [9], [10]. Those lasers, however, were bulky dye or Nd : YAG lasers and their handling required special skills, thus, their application to measurement was the preserve of optical engineers and of physicists studying ultrafast phenomena. In the 1990's, with the development of easy-to-use semiconductor lasers and such other photonic components as detectors and modulators, photonic measurement techniques have made remarkable progress, becoming accessible to a broader range of people including electrical engineers and circuit designers.

This paper describes recent practical instrumentation and measurement technologies, based on 1.55-μm photonics that cover the frequency range from microwaves to millimeter waves. Firstly, the basic technologies used in measurement, namely, the generation, transmission, and detection of high-frequency microwave signals, are described. This is followed by a description of the real-world application of these techniques to contemporary device/IC testers, sampling oscilloscopes, network analyzers, a free-space electric-field sensor, and an imaging system.

II. Basic Technologies

The basic idea of a photonic measurement system is shown in Fig. 1 [11], [12]. An optical-to-electrical (O–E) converter generates electrical signals, which are transmitted, as a stimulus, through free space or a waveguide to a device-under-test (DUT). A probe consisting of an electrical-to-optical transducer then optically detects the electrical response of the DUT. Here, lossy

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T. Nagatsuma, M. Shinagawa, A. Sasaki, and A. Hirata are with the NTT Telecommunications Energy Laboratories, Atsugi, Kanagawa 243-0198, Japan (e-mail: ngtm@aecl.ntt.co.jp).

N. Sahri was with the NTT Telecommunications Energy Laboratories, Atsugi, Kanagawa 243-0198, Japan. He is now with the Alcatel OPTO+ Corporate Research Center, F-91461 Marcoussis Cedex, France.

Y. Royter was with the NTT Telecommunications Energy Laboratories, Atsugi, Kanagawa 243-0198, Japan. He is now with HRL Laboratories, Malibu, CA 90265 USA.

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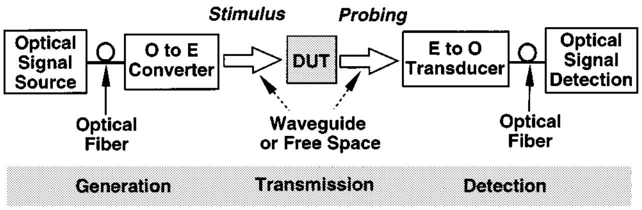


Fig. 1. Illustration of the concept applied in measurement systems based on photonic techniques.

coaxial cables and bulky metallic waveguides for delivering and receiving high-frequency electrical signals are replaced with optical fiber cables. In the following, we describe technologies based on the application of 1.55-μm optical wavelengths, which have become more practical than those based on visible or near-infrared wavelengths, although systems of the latter type were rather common in the initial phases of such research.

A. Optical Signal Sources

For both generation and detection, producing optical pulses and sinusoids is one of the key technologies for practical instrumentation. The advent of semiconductor laser diodes, pulse compression, and optical amplification has given us femtosecond lasers that provide turnkey and maintenance-free operation in rack-mounted or board-packaged equipment. The most promising technologies for pulse sources are a gain-switched laser diode [13] and a mode-locked fiber laser [14], both of which are used with a fiber-optic pulse compressor. Optical pulses of <300 fs in duration with an average power of >10 mW are easily obtained with these techniques.

In particular, the gain-switched laser diode is more suitable for measurement applications than the mode-locked laser since it can be operated at any repetition frequency by simply changing the frequency of an electrical pulse generator that drives the diode. To reduce the timing jitter to much less than 1 ps, a dc light source is injected into the laser [13]. In the case of pulse compression using optical fibers, pedestals often arises along with the main pulse, and they degrade the effective bandwidth or temporal resolution of the measurement [15]. A nonlinear switching element such as a nonlinear optical loop mirror reduces pedestals to less than 0.01% of the main pulse [16].

As for sinusoidal or quasi-sinusoidal sources, we can use a mode-locked laser diode (MLLD) integrated with saturable absorbers [17]–[21] and heterodyne laser mixing [22]–[24]. Operation and stabilization schemes are of two main types for MLLDs: an active MLLD with electrical injection [17], [18] and a passive one with optical injection [19]–[21]. With either scheme, >100-GHz signals with subharmonic injection frequencies can be generated, as long as the fundamental frequency is within the capability of a microwave synthesizer, i.e., from 10 to 50 GHz.

Optical heterodyne mixing employs the beat signal from the interference of two optical frequencies. This scheme allows us to easily extend the frequency range up into the terahertz regime with greater tunability of frequency. When two single-frequency (wavelength) lasers are used, the phase locking of the two lasers is crucial to obtaining sufficiently narrow spectral linewidths. The combination of a fiber laser and an external cavity semiconductor laser is one of the best options to achieve a high degree of spectral purity over a broad frequency range [22]. The selection of two lines from a single laser that produces lines at multiple wavelengths, such as a Fabry–Perot laser diode, a mode-locked laser, and an optical comb generator, is an easier and simpler way to generate stable beat signals [23], [24].

B. Stimulus

Electrical signals as stimulus are generated by converting sinusoidal or pulsed optical signals to electrical signals, and they are delivered to the DUT via an antenna or transmission line. As for O–E converters, the bandwidths and output power levels of p-i-n photodiode (PDs) have recently been greatly improved through the use of waveguide, traveling-wave and distributed structures [25], [26], and novel carrier dynamics [27]. Of these, a unitraveling carrier photodiode (UTC-PD) [27], [28] is unique in that it provides both a large bandwidth and a high output current. In its operation, only electrons are used as active carriers, and hole transport directly affects neither its PD response, nor its mechanisms of the output saturation. The smallest pulsewidth obtained to date is 0.97 ps, and this corresponds to a 3-dB bandwidth of 310 GHz [29]. Using a UTC-PD and an MLLD, a 60-GHz continuous wave (CW) with an output power of 12 dBm has been obtained [11]. This is comparable to the performance of solid-state electronic devices.

Fig. 2 shows two examples of fiber-optic electrical signal generators that employ UTC-PDs. In Fig. 2(a), an O–E conversion probe head for triggering electronic devices and ICs on wafer is formed by bonding the UTC-PD to a coplanar waveguide made on a quartz substrate [30]. Fig. 2(c) shows the pulse response of the probe head as measured with an electrooptic (EO) probing technique that is described below under “probing.” The 3-dB bandwidth of the probe is >100 GHz. The peak output voltage is 900 mV, which is high enough to directly drive digital ICs.

A free-space millimeter-wave emitter [31], [32] for wireless applications is shown in Fig. 2(b). The UTC-PD chip is flip-chip mounted on a planar slot antenna on a silicon substrate. The antenna chip is bonded to a hemispherical silicon lens in order to collimate millimeter-wave signals in the direction opposite that of the illumination. At 120 GHz, >1 mW was generated in the PD chip and hundreds of microwatts were emitted into free space. The integration of an planar antenna with the PD is an effective way to reduce feedline losses [33], [34].

C. Probing

In probing applications, the electrical signal is detected by an electrical-to-optical transducer in combination with an optical signal source. Signal detection techniques are based on the interaction between optical and microwave signals. The physical phenomenon involved can be an EO effect [35], a photoconductive (PC) effect [36], an electro-absorption (EA) effect [37], or a magnetooptic (MO) effect [38], [39].

Among these, optical sampling on the basis of an EO effect, or EO probing, has become the most common in various types of measurement tools and instrumentation because it has the highest temporal resolution and is easy to use at long optical wavelengths. The typical configurations for the EO measurement of electrical signals propagating on transmission lines in

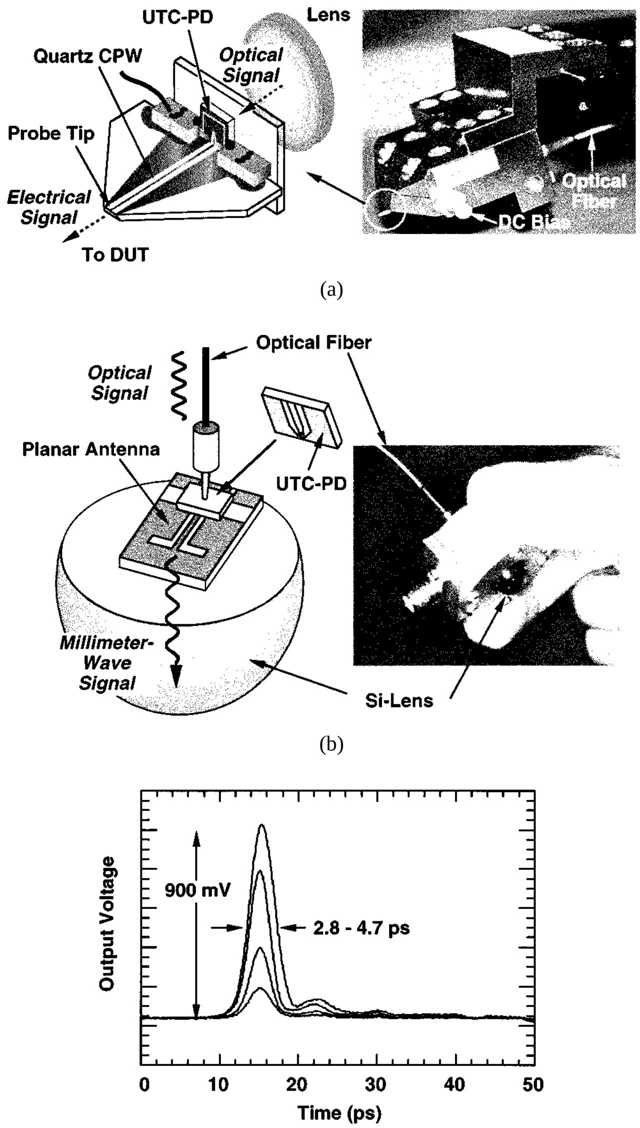


Fig. 2. Two microwave-signal generators based on photonic techniques. (a) Stimulus O–E probe head for testing electronic devices on wafer. (b) Millimeter-wave signal emitter for free-space applications. (c) Measured electrical pulses generated by the O–E probe head.

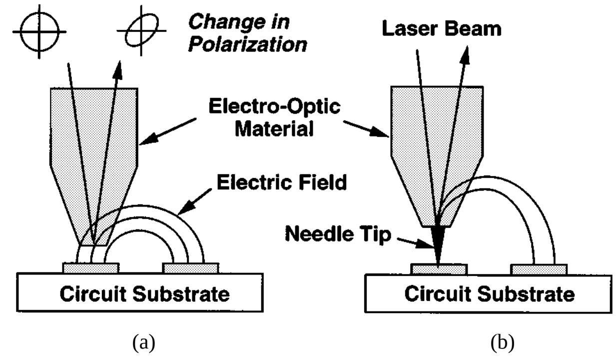


Fig. 3. Typical configuration for IC measurement based on EO probing. (a) Noncontact fringing-field sensing. (b) Contact potential sensing.

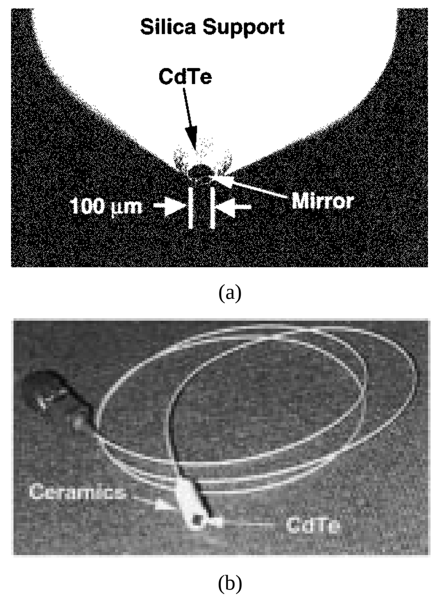


Fig. 4. EO sensor heads for: (a) internal IC testing and (b) free-space applications.

ICs or printed circuit boards are shown in Fig. 3. The polarization of the laser beam reflecting off the bottom of the EO material (typically a crystal) changes with the intensity of the electric field coupled to the material. In some measurement applications, a tiny needle tip is attached to the EO materials to obtain a voltage measurement or a submicrometer spatial resolution. When, however, bandwidths of $>$100 GHz must be handled, the fringing electric field is sensed without using the needle tip.

Fig. 4 shows examples of actual sensors made of CdTe crystals; a probe tip used for internal IC testing [(100)-cut crystal] [40] and a fiber-optic sensor for detecting a free-space electric field [(110)-cut crystal] [11]. There is little choice in EO materials appropriate for the electric-field sensors. The commonly used crystals are $LiTaO_3$, KTP, ZnTe, CdTe GaAs, and BSO. The development of EO materials with much higher (at least one order of magnitude higher) EO coefficients is one of the most crucial issues for further progress in this area.

Either CW [41] or pulse laser sources can be applied as optical sources in EO probing, but pulse lasers are more common. This is because, in combination with a sampling scheme, they are capable of higher bandwidths.

D. Transmission

The efficient propagation of signals between the generation/detection points and the DUT must be realized either through transmission lines, or through free space with the aid of radiating elements such as antennas. An innovative fabrication process that allows us to realize low-loss/dispersion transmission lines capable of carrying millimeter-wave signals even on lossy semiconductor substrates has recently been developed [42]–[47]. Fig. 5 shows a sidewall coplanar waveguide made on an Si substrate, which is usable at frequencies of $>$100 GHz [44], [45]. The V-shaped groove and thick metallization is effective in reducing the substrate and conductor losses and dispersion. Most of the electric field is concentrated between the conductor's sidewalls.

Moreover, the monolithic integration of O–E converters (i.e., PDs) with millimeter-wave transmission lines or antennas on the

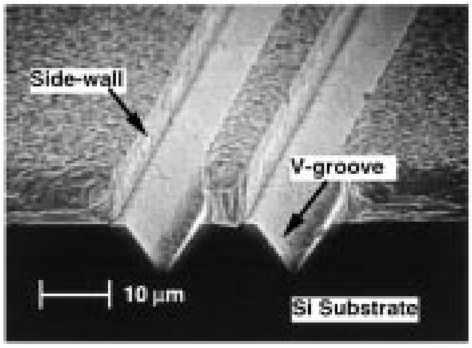


Fig. 5. Photograph of a millimeter-wave coplanar waveguide made by an Si-micromachined process.

same substrate has been successfully demonstrated. By eliminating the process of bonding the components, this approach improves ease of manufacture and performance [46]–[50].

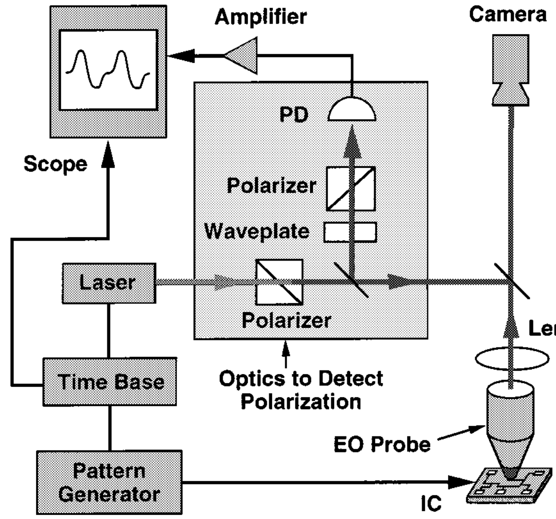
III. Practical Realizations

A. Device/IC Probing System

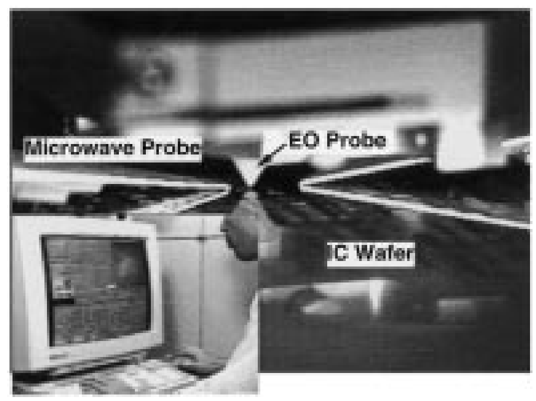
The most mature real-world application of photonic measurements is the characterization and testing of ultrahigh-speed devices and ICs. The approaches used are based on EO and PC sampling techniques [40], [51]–[53]. Fig. 6(a)–(c) shows a typical configuration for measuring internal-node voltage waveforms in ICs on the basis of EO sampling, photographs of the IC prober at work [54], and an example of waveforms measured from a communications IC operating at 20 Gb/s, respectively. Minimum detectable voltages in such applications are typically 100 μV–1 mV.

In addition to the features particular to the use of these photonic techniques, i.e., wide bandwidth (>1 THz), high temporal resolution (<0.3 ps), and a low degree of invasiveness, two recent developments have made further features available. One is a combination with scanning probe microscopy that offers extremely fine spatial resolution (<100-nm resolution) [55]. This form of EO probing has been applied to CMOS-based ultra-large scale integrated circuits (ULSIs) of the current generation, i.e., with submicrometer linewidth. To access the lowest level conductors in large-scale integrated circuits (LSIs) with multilevel interconnections, a focused ion beam was used to make tungsten via-holes and pads especially for EO probing [56]. The other new feature is two-dimensional field mapping [57], [58]. A photonic field-probing technique is less invasive than inductive probing and makes higher spatial resolutions possible. Thus, it could become a very powerful tool for MMIC diagnosis when used in combination with state-of-the-art electromagnetic-field simulators, which solve Maxwell's equations by using, for instance, the finite-element and finite-difference time-domain methods.

Along with the passive probing of electrical signals generated by or propagating on a device/IC, photonic techniques can be used to supply high-frequency signals to the DUT for active testing. In this configuration, an integrated O–E conversion probe head [see Fig. 2(a)] with optical signal sources is used to inject patterns of electrical signals, as well as impulse signals to the DUT at frequencies of over 100 GHz [59], [60].



(a)



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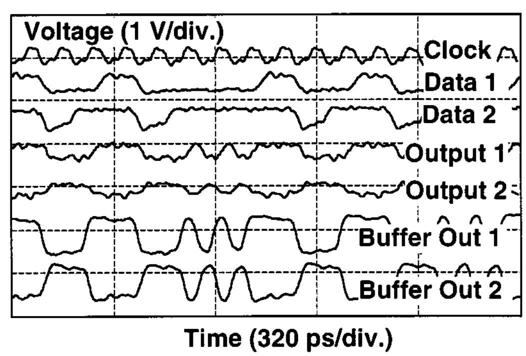

(c)

Fig. 6. (a) Typical configuration for measuring internal-node voltage waveforms in ICs based on EO probing. (b) Photographs of an automated IC prober. (c) Example of measured internal waveforms of a communications IC.

B. Handheld Probes

Fig. 7 shows a handheld probe for circuit-board and module measurement. All of the photonic components required for EO probing are integrated into the probe [61], [62]. Probes of two types have been developed and are both now commercially available. One is a sampling oscilloscope using a pulse laser [see Fig. 7(a)] [61], and the other is a real-time probe unit with a CW laser [see Fig. 7(b)] [62]. The latter unit is employed with

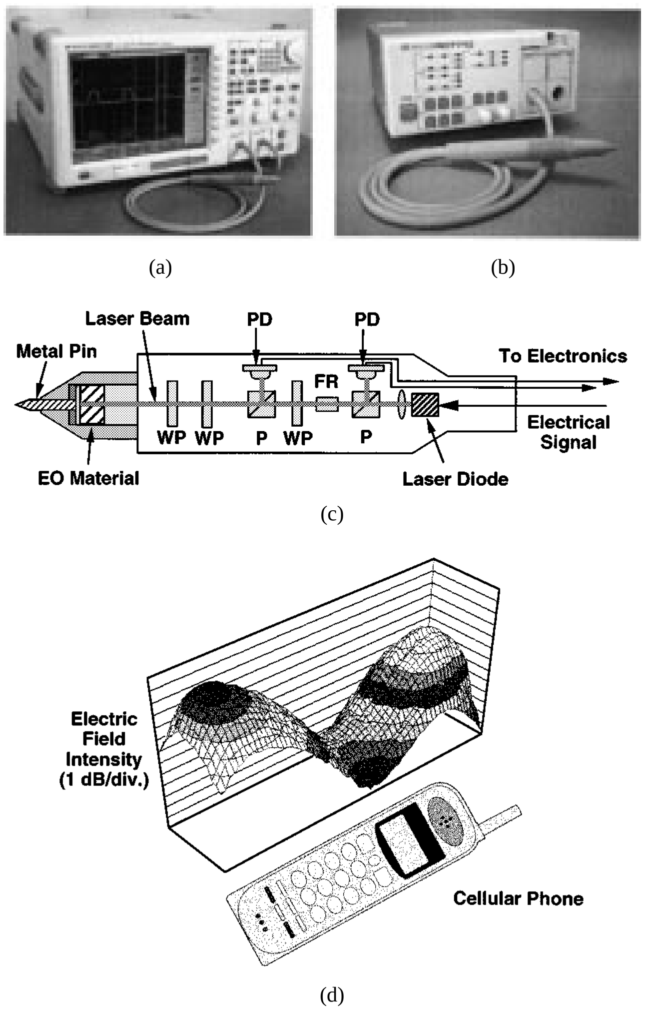

Fig. 7. Two handheld high-impedance probes. (a) EO digital sampling oscilloscope. (b) Real-time EO probe unit. (c) Block diagram of the typical probe head. (d) Distribution of electric field radiating from a cellular phone during a call, as measured with the probe in (b). WP: waveplate, P: polarizer, FR: Faraday rotator.

a conventional electronic sampling oscilloscope or a spectrum analyzer. The unique features of these probes are a larger bandwidth, a higher input impedance, single-contact, i.e., no ground-contact operation, and a high degree of immunity to electrostatic discharge.

One of the most recent applications of the probe is to the measurement of the electromagnetic interference (EMI). By bringing the probe close to objects that are emitting radio waves, we can measure the radiation patterns of radio waves. The measured electric-field intensity distribution for a cellular phone with a call in progress is shown in Fig. 7(d). Similar techniques led to the successful measurement of the two-dimensional radiation field from planar antennas [63], [64]. Several types of optical sensors for measuring electric fields, as well as magnetic fields, have been developed with practical design and features [39], [65], [66].

C. Network Analyzer

There is now an urgent need for a millimeter-wave broadband network analyzer since the upper frequencies of conventional vector network analyzers are limited to 110 GHz for *full-band* operation (continuously from a few tens of megahertz to millimeter-wave frequencies), and they only can operate in the linear or small-signal regime. This frequency limit can be extended to upper millimeter-wave[1] and submillimeter-wave frequencies,[2] although several sets of transmitter/receiver modules with relatively narrow bandwidths have to be prepared to fully cover the continuous frequency range of interest.

Against this background, we have developed a novel millimeter-wave network analyzer that enables a full-band measurement only with a single setup. Fig. 8(a) illustrates the head of the ultrabroad-band network analyzer, based on time-domain photonic techniques. All the functions of stimulus, sampling, and bias for the DUT are integrated into a probe head structure dedicated to measuring the two-port scattering (S-) parameters of devices [14], [67]. This implementation of techniques for generation, transmission, and detection in a single device is the fullest realization of the concept of photonic measurement shown in Fig. 1.

An effective measurement bandwidth of $>$300 GHz was obtained and the system was used to characterize $>$100-GHz high electron-mobility transistors (HEMTs) with excellent reproducibility of measurement, as is shown in Fig. 8(c). Data obtained with a conventional 40-GHz network analyzer were shown for comparison. The results agree quite well, with the only major discrepancy being for $S12$ at low frequencies. This arises because the current photonic network analyzer is not sensitive enough, i.e., the lowest signal level was clipped to around -30 dB. Additional work is under way to enhance the accuracy of the system by increasing the sensitivity or dynamic range and by using proper calibration.

D. Free-Space Applications

Here, we show two new free-space applications using photonic millimeter-wave emitters and/or detectors.

The experimental setup for measuring the electric field radiated into free space from a photonic emitter (a combination of a PD and an antenna) is depicted in Fig. 9 [11]. A UTC-PD is excited by an MLLD to generate a 60-GHz millimeter-wave signal, and the radiating waveform is measured with the EO sensor head [see Fig. 4(b)]. Here, the MLLD is phase locked to the passively mode-locked fiber laser, which is used as the sampling-pulse source. In this figure, traces of the measured electric field for different photocurrents of the UTC-PD are shown. The system's minimum detectable power level is -40 dBm.

This is also the model for the millimeter-wave photonic wireless communication systems of the future. Most recently, a photonic emitter operating at 120 GHz has successfully been used to transmit video signals [31], and a wireless link for multigigabit/s signals will be feasible in the near future.

When we insert an object between the emitter and detector, we are able to perform millimeter-wave imaging. Imaging using

[1]Model V05VNA-T/R (140–220GHz), Oleson Microwave Laboratories, Morgan Hill, CA.

[2]Model MVNA 8-350 with options ESA, AB Millimeter, Paris, France.

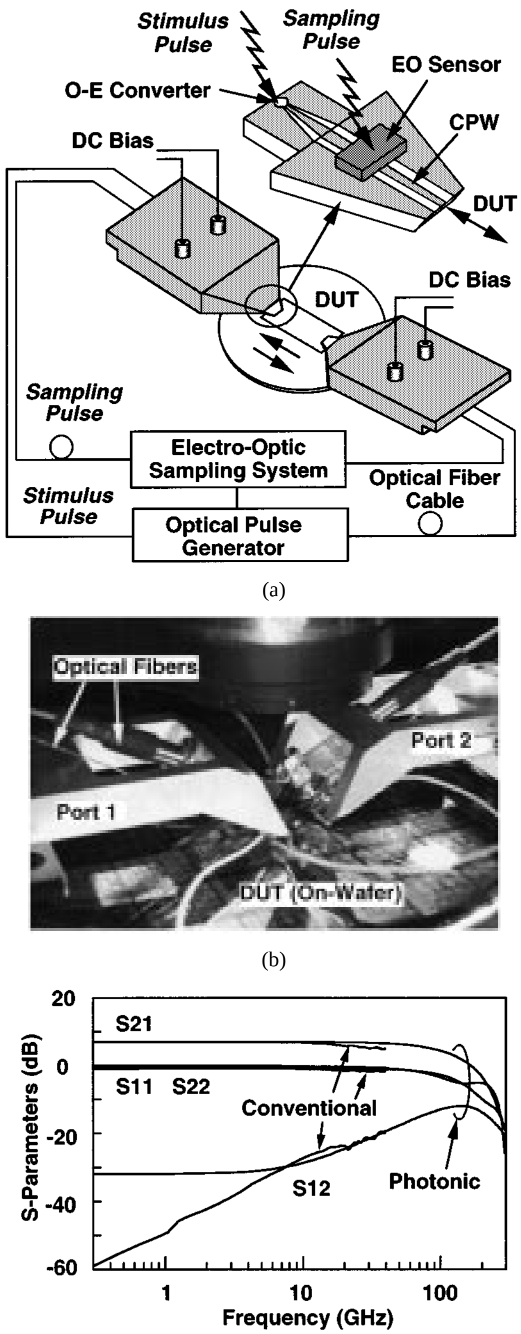

Fig. 8. Photonic millimeter-wave network analyzer. (a) System configuration. (b) Pair of probes accessing a device on wafer. (c) Comparison of the magnitudes of S-parameters as obtained by a photonic measurement system and measurement with a conventional 40-GHz-bandwidth network analyzer.

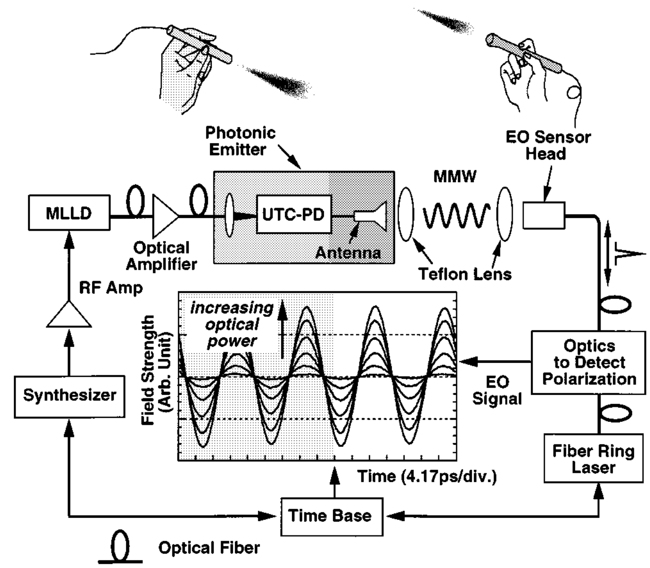

Fig. 9. Experimental setup for wireless millimeter-wave transmission based on all-photonic techniques.

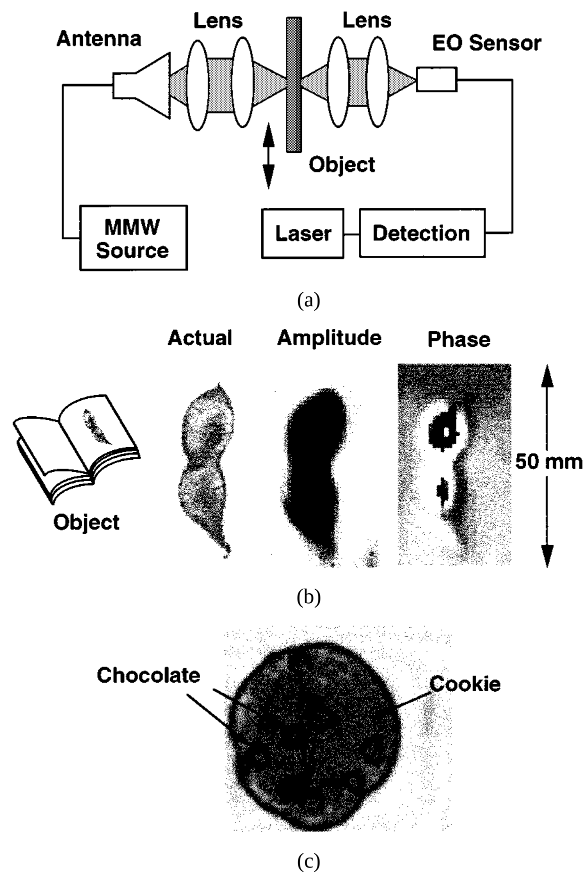

Fig. 10. Millimeter-wave imaging using photonic techniques. (a) Experimental setup. (b) Obtained image of soybeans. (c) Obtained image of a chocolate-chip cookie in its package.

electromagnetic waves in the millimeter to submillimeter wavelength range is useful in obtaining information, e.g., through clouds, smoke, dust, and other screening conditions, for which visible, IR, and X-ray systems are ineffective. The imaging using photonically generated pulsed or single-cycle electromagnetic waves with a subpicosecond duration has recently been extensively studied [68], [69]. Such imaging is often referred to as T-ray imaging. Possible areas of application are inspection of the materials and package, spectroscopy of gases, solids and liquids, and semiconductor imaging. This covers a wide range of fields, including science, biomedicine, industry, electronics, and quality control.

Fig. 10 shows another type of photonic imaging system in which continuous millimeter waves are applied. The millimeter-wave signal transmitted through the object is detected by the EO sensor head [70]. The object shown in Fig. 10(b) is a green soybean pod, placed in a booklet a few millimeters thick. We managed to obtain an image of the object at 100 GHz. While only the contours of the pod are visible with amplitude detection, the beans inside the envelope become visible with phase detection. Fig. 10(c) shows an image of a package of chocolate-chip cookies. Thus, we get a good view of the distribution of chocolate chips without having to open the package.

In the future, the combination of frequency-tunable photonic millimeter-wave emitters and EO-based broad-band detection will make a spectroscopic imaging camera feasible.

IV. Conclusion

We have reviewed recent progress in instrumentation and measurement based on ultrafast photonic technologies. Progress has been accelerated in recent years, in particular, by the use of 1.55-μm semiconductor lasers, detectors, and fiber-optic components. These are essential to making modules and systems that are compact and stable. These technologies have already enabled us to cover the frequency range from 30 to 300 GHz, and will allow us to reach the terahertz range in the future.

The use of photonic technologies has proven to be very useful, and various instruments such as IC testers and sampling oscilloscopes are already on the market. The required optical components are still, however, much larger and costlier than those of equivalent electronic systems. In the future, the focus on the development of photonic instrumentation and measurement must be on integration and packaging to achieve lower costs, smaller devices, and greater levels of functionality.

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References

[1] M. J. W. Rodwell, Q. Lee, D. Mensa, J. Guthrie, Y. Bester, S. C. Martin, R. P. Smith, S. Jaganathan, T. Mathew, P. Krishnan, C. Serhan, and S. Long, "Heterojunction bipolar transistors with greater than 1 THz extrapolated power-gain cutoff frequencies," in *Proc. IEEE Int. Terahertz Electron. Conf.*, 1999, pp. 120–123.

[2] T. Otsuji, "Present and future of high-speed electronic devices and IC's," in *MWE 2000 Microwave Workshop Dig.*, 2000, pp. 237–242.

[3] M. J. W. Rodwell, S. T. Allen, R. Y. Yu, M. G. Case, U. Bhattacharya, M. Reddy, E. Carman, M. Kamegawa, Y. Konishi, J. Pusl, and R. Pullela, "Active and nonlinear wave propagation devices in ultrafast electronics and optoelectronics," *Proc. IEEE*, vol. 82, pp. 1037–1059, July 1994.

[4] U. Bhattacharya, S. T. Allen, and M. J. W. Rodwell, "DC–725 GHz sampling circuits and subpicosecond nonlinear transmission lines using elevated coplanar waveguide," *IEEE Microwave Guided Wave Lett.*, vol. 5, pp. 50–52, Feb. 1995.

[5] R. Y. Yu, M. Reddy, J. Pusl, S. T. Allen, M. Case, and M. J. W. Rodwell, "Millimeter-wave on-wafer waveform and network measurements using active probes," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 721–729, Apr. 1995.

[6] O. Wohlgemuth, M. J. W. Rodwell, R. Reuter, J. Braunstein, and M. Schlechtweg, "Active probes for network analysis within 70–230 GHz," *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 2591–2598, Dec. 1999.

[7] H. Eisele, "Two-terminal devices as fundamental solid-state terahertz oscillators," in *Proc. SPIE EUROOPTO Terahertz Spectroscopy Applicat. Conf.*, vol. 3828, 1999, pp. 70–80.

[8] P. F. Goldsmith, *Quasioptical Systems: Gaussian Beam Quasioptical Propagation and Applications*. Piscataway, NJ: IEEE Press, 1998.

[9] K. J. Weingarten, M. J. W. Rodwell, and D. M. Bloom, "Picosecond optical sampling of GaAs integrated circuits," *IEEE J. Quantum Electron.*, vol. 24, pp. 198–220, Feb. 1988.

[10] R. B. Marcus, Ed., "Measurement of high-speed signals in solid-state devices," in *Semiconductors and Semimetals*. New York: Academic, 1990, vol. 28.

[11] T. Nagatsuma, N. Sahri, M. Yaita, T. Ishibashi, N. Shimizu, and K. Sato, "All optoelectronic generation and detection of millimeter-wave signals," in *Microwave Photon. Tech. Dig.*, 1998, pp. 5–8.

[12] T. Nagatsuma, "Progress of instrumentation and measurement toward millimeter-wave photonics," in *Microwave Photon. Tech. Dig.*, 1999, pp. 91–94.

[13] N. Sahri, T. Nagatsuma, M. Yaita, and N. Shimizu, "Picosecond synchronous electro-optic sampling with a jitter-reduced gain-switched laser diode," *Jpn. J. Appl. Phys.*, vol. 37, pp. L39–L41, 1998.

[14] N. Sahri and T. Nagatsuma, "Application of 1.55-μm photonic technologies to practical millimeter-wave network analyzer," *IEICE Trans. Electron.*, vol. E82-C, pp. 1307–1311, 1999.

[15] M. Yaita and T. Nagatsuma, "The effect of sampling-pulse pedestals on temporal resolution in electro-optic sampling," *IEICE Trans. Electron.*, vol. E81-C, pp. 254–259, 1998.

[16] K. R. Tamura and M. Nakazawa, "Spectral-smoothing and pedestal reduction of wavelength tunable quasi-adiabatically compressed femtosecond solitons using a dispersion-flatted dispersion-imbalanced loop mirror," *IEEE Photon. Technol. Lett.*, vol. 11, pp. 230–232, Feb. 1999.

[17] K. Sato, I. Kotaka, Y. Kondo, and M. Yamamoto, "Active mode locking at 50 GHz repetition frequency by half-frequency modulation of monolithic semiconductor lasers integrated with electroabsorption modulators," *Appl. Phys. Lett.*, vol. 69, pp. 2626–2628, 1996.

[18] K. Sato, I. Kotaka, A. Hirano, M. Asobe, Y. Miyamoto, N. Shimizu, and K. Hagimoto, "High-repetition frequency pulse generation at 102 GHz using mode-locked lasers integrated with electroabsorption modulators," *Electron. Lett.*, vol. 34, pp. 790–792, 1998.

[19] S. Arahira, Y. Matsui, and Y. Ogawa, "Mode-locking at very high repetition rates more than terahertz in passively mode-locked distributed-Bragg reflector laser diodes," *IEEE J. Quantum Electron.*, vol. 32, pp. 1211–1224, July 1996.

[20] S. Arahira, Y. Katoh, D. Kunimatsu, and Y. Ogawa, "Stabilization and timing jitter reduction of 160-GHz colliding-pulse mode-locked laser diode by subharmonic-frequency optical pulse injection," *IEICE Trans. Electron.*, vol. E83-C, pp. 966–973, 2000.

[21] Y. J. Wen, D. Novak, H. F. Liu, and A. Nirmalathas, "Generation of 140-GHz optical pulses with suppressed amplitude modulation by subharmonic synchronous modelocking of Fabry–Perot semiconductor," *Electron. Lett.*, vol. 37, pp. 581–582, 2001.

[22] J. Payne, B. Shillue, and A. Vaccari, "Photonic techniques for use on the Atacama large millimeter array," in *Microwave Photon. Tech. Dig.*, 1999, pp. 105–108.

[23] E. A. Swanson, S. R. Chinn, K. Hall, K. A. Rauschenbach, R. S. Bondurant, and J. W. Miller, "100-GHz soliton pulse train generation using soliton compression of two phase side bands from a single DFB laser," *IEEE Photon. Technol. Lett.*, vol. 6, pp. 1194–1196, Oct. 1994.

[24] O. P. Gough, C. F. C. Silvia, and A. J. Seeds, "Exact millimeter-wave frequency synthesis by injection locked laser comb line selection," in *Microwave Photon. Tech. Dig.*, 1999, pp. 61–64.

[25] A. Stöhr, R. Heinzekmann, C. Kaczmarek, and D. Jäger, "Ultra-broadband Ka- to W-band 1.55-μm travelling-wave photomixers," *Electron. Lett.*, vol. 36, pp. 970–971, 2000.

[26] T. Chau, N. Kaneda, T. Jung, A. Rollinger, S. Mathai, Y. Qian, T. Itoh, M. C. Wu, W. P. Shillue, and J. M. Payne, "Generation of millimeter waves by photomixing at 1.55 μm using InGaAs–InAlAs–InP velocity-matched distributed photodetectors," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 1055–1057, Aug. 2000.

[27] T. Ishibashi, N. Shimizu, S. Kodama, H. Ito, T. Nagatsuma, and T. Furuta, "Uni-traveling-carrier photodiodes," in *Ultrafast Electron. Optoelectron. Tech. Dig.*, 1997, pp. 83–87.

[28] T. Ishibashi, T. Furuta, H. Fushimi, S. Kodama, H. Ito, T. Nagatsuma, N. Shimizu, and Y. Miyamoto, "InP/InGaAs uni-traveling-carrier photodiodes," *IEICE Trans. Electron.*, vol. E83-C, pp. 938–949, 2000.

[29] H. Ito, T. Furuta, S. Kodama, and T. Ishibashi, "InP/InGaAs uni-traveling-carrier photodiode with 310-GHz bandwidth," *Electron. Lett.*, vol. 39, pp. 1809–1810, 2000.

[30] T. Otsuji, N. Sahri, N. Shimizu, T. Nagatsuma, and T. Ishibashi, "A 105-GHz bandwidth optical-to-electrical conversion stimulus probe head employing a unitraveling-carrier photodiode," *IEEE Photon. Technol. Lett.*, vol. 11, pp. 1033–1035, Aug. 1999.

[31] T. Nagatsuma, A. Hirata, Y. Royter, M. Shinagawa, T. Furuta, T. Ishibashi, and H. Ito, "A 120-GHz integrated photonic transmitter," in *Microwave Photon. Tech. Dig.*, 2000, pp. 225–228.

[32] A. Hirata, "Design and characterization of millimeter-wave antenna for integrated photonic emitter," in *Proc. Asia–Pacific Microwave Conf.*, 2000, pp. 70–73.

[33] B. Ke, T. Chau, Y. Qian, M. Wu, and T. Itoh, "Tapered slot antenna with velocity-matched distributed photodetector," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1999, pp. 1241–1244.

[34] G. A. Chakam and W. Freude, "Coplanar phased array antenna with optical feeder and photonic bandgap structure," in *Microwave Photon. Tech. Dig.*, 1999, pp. 1–4.

[35] J. A. Valdmanis, G. Mourou, and C. W. Gabel, "Subpicosecond electro-optic sampling," *IEEE J. Quantum Electron.*, vol. QE-19, pp. 664–667, Apr. 1983.

[36] D. H. Auston, "Picosecond optoelectronic switching and gating in silicon," *Appl. Phys. Lett.*, vol. 26, pp. 101–103, 1975.

[37] T. Nagatsuma, M. Yaita, and K. Iwatsuki, "Optical signal measurement using electro-absorption sampling," in *Ultrafast Electron. Optoelectron. Tech. Dig.*, 1997, pp. 172–174.

[38] J. A. Riordan, F. G. Sun, Z. G. Lu, and X.-C. Zhang, "Free-space transient magneto-optic sampling," *Appl. Phys. Lett.*, vol. 71, pp. 1452–1454, 1997.

[39] S. Wakana, T. Ohara, M. Abe, E. Yamazaki, M. Kishi, and M. Tsuchiya, "Fiber-edge electrooptic/magnetooptic probe for spectral-domain analysis of electromagnetic field," *IEEE Trans. Microwave Theory Tech.*, vol. 48, pp. 2611–2616, Dec. 2000.

[40] T. Nagatsuma, "Electro-optic testing technology for high-speed LSIs," *IEICE Trans. Electron.*, vol. E79-C, pp. 482–488, 1996.

[41] Z. H. Chu, C. L. Pan, Y. H. Lo, M. C. Wu, S. Wang, B. H. Kolner, and S. Y. Wang, "Electro-optic measurement of standing waves in a GaAs coplanar waveguide," *Appl. Phys. Lett.*, vol. 50, pp. 1228–1230, 1987.

[42] K. J. Herrick, J.-G. Yook, and L. P. B. Katehi, "Microtechnology in the development of three-dimensional circuits," *IEEE Trans. Microwave Theory Tech.*, vol. 46, pp. 1832–1844, Nov. 1998.

[43] J. Kim, Y. Qian, G. Feng, P. Ma, M. F. Chang, and T. Itoh, "Millimeter-wave silicon MMIC interconnect and coupler using multilayer polyimide technology," *IEEE Trans. Microwave Theory Tech.*, vol. 48, pp. 1482–1487, Sept. 2000.

[44] N. Sahri, T. Nagatsuma, K. Machida, H. Ishii, and H. Kyuragi, "Characterization of micromachined coplanar waveguides on silicon up to 300 GHz," in *Proc. European Microwave Conf.*, 1999, pp. 254–257.

[45] H. Ishii, N. Sahri, T. Nagatsuma, K. Machida, K. Saito, S. Yagi, M. Yano, K. Kudo, and H. Kyuragi, "New fabrication process for low-loss millimeter-wave transmission lines on silicon," *Jpn. J. Appl. Phys.*, vol. 39, pp. 1982–1986, 2000.

[46] Y. Royter, T. Minotani, H. Ishii, A. Hirata, S. Yagi, K. Machida, T. Furuta, T. Ishibashi, A. Sasaki, and T. Nagatsuma, "Ultrahigh-speed 1.55-μm photodiodes on Si with low-loss millimeter-wave waveguides," in *IEEE LEOS Tech. Dig.* , 2000, pp. 283–284.

[47] T. Minotani, Y. Royter, H. Ishii, A. Hirata, K. Machida, A. Sasaki, and T. Nagatsuma, "Three-dimensional millimeter-wave photonic integrated circuits on Si," in *IEEE MTT-S Int. Microwave Symp. Dig.* , 2001, pp. 57–60.

[48] N. M. Jokerst, M. A. Brooke, J. Lasker, D. S. Wills, A. S. Brown, M. Vrazel, S. Jung, Y. Joo, and J. J. Chang, "Microsystem optoelectronic integration for mixed multisignal systems," *IEEE J. Select. Topics Quantum Electron.*, vol. 6, pp. 1231–1239, Nov.–Dec. 2000.

[49] Y. H. Lo, Z. H. Zhu, Y. Qian, F. E. Ejeckam, and G. L. Christenson, "Wafer-bonding technology and its optoelectronic applications," in *Proc. SPIE Optoelectron. Integrated Circuits*, vol. 3006, 1997, pp. 26–35.

[50] Y. Royter, T. Furuta, S. Kodama, N. Sahri, T. Nagatsuma, and T. Ishibashi, "Integrated packaging of over 100 GHz bandwidth uni-traveling-carrier photodiodes," *IEEE Electron. Device Lett.*, vol. 21, pp. 158–160, Apr. 2000.

[51] T. Nagatsuma, "Measurement of high-speed devices and integrated circuits using electro-optic sampling techniques," *IEICE Trans. Electron.*, vol. E76-C, pp. 55–63, 1993.

[52] *Opt. Quantum Electron. (Special Issue)*, vol. 28, 1996.

[53] T. Pfeifer, H.-M. Heiliger, T. Löffler, C. Ohlhoff, C. Meyer, G. Lüpke, H. G. Roskos, and H. Kurz, "Optoelectronic on-chip characterization of ultrafast electronic devices: Measurement techniques and applications," *IEEE J. Select. Topics Quantum Electron.*, vol. 2, pp. 586–604, Sept. 1996.

[54] M. Shinagawa and T. Nagatsuma, "An automated electro-optic probing system for ultrahigh-speed IC's," *IEEE Trans. Instrum. Meas.*, vol. 43, pp. 843–847, Dec. 1994.

[55] K. Ozaki, H. Sekiguchi, S. Wakana, Y. Goto, Y. Umehara, and J. Matsumoto, "Novel optical probing system with submicron spatial resolution for internal diagnosis of VLSI circuits," in *Proc. Int. Test Conf.*, 1996, pp. 269–275.

[56] C. Hashimoto, T. Takizawa, S. Nakajima, M. Shinagawa, and T. Nagatsuma, "Observation of the internal waveforms in high-speed high-density LSI's using an EOS prober," *Microelectron. Reliab.*, to be published.

[57] G. David, R. Tempel, I. Wolff, and D. Jäger, "Analysis of microwave propagation effects using 2-D electro-optic field mapping techniques," *Opt. Quantum Electron.*, vol. 28, pp. 919–931, 1996.

[58] K. Yang, G. David, S. V. Robertson, J. F. Whitaker, and L. P. B. Katehi, "Electrooptic mapping of near-field distributions in integrated microwave circuits," *IEEE Trans. Microwave Theory Tech.*, vol. 46, pp. 2338–2343, Dec. 1998.

[59] T. Otsuji, T. Nagatsuma, K. Kato, and M. Yoneyama, "Widely tunable electrooptic pulse-pattern generation and its application to on-wafer large-signal characterization of ultrahigh-speed electronic devices," *Opt. Quantum Electron.*, vol. 28, pp. 991–1005, 1996.

[60] T. Otsuji, K. Kato, S. Kimura, and T. Nagatsuma, "Wide-band high-efficiency optical-to-electrical conversion stimulus probe heads for testing large-signal response of high-speed electronic devices," *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 525–533, May 1999.

[61] M. Shinagawa and T. Nagatsuma, "A novel high-impedance probe for multi-gigahertz signal measurement," *IEEE Trans. Instrum. Meas.*, vol. 45, pp. 575–579, Apr. 1996.

[62] M. Shinagawa, T. Nagatsuma, K. Ohno, and Y. Jin, "A real-time electro-optic handy probe using a CW laser," in *Proc. IEEE Instrum. Meas. Technol. Conf.*, 2000, pp. 1541–1546.

[63] Y. Imaizumi, M. Shinagawa, and H. Ogawa, "Electric field distribution measurement of microstrip antennas and arrays using electro-optic sampling," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 2402–2047, Sept. 1995.

[64] K. Yang, L. P. B. Katehi, and J. F. Whitaker, "Electro-optic field mapping system utilizing external gallium–arsenide probes," *Appl. Phys. Lett.*, vol. 77, pp. 486–488, 2000.

[65] A. Stöhr, R. Heinzekmann, T. Alder, D. Kalinowsli, M. Gross, and D. Jäger, "Integrated optical E-field sensors using TW EA-modulators," in *Int. Topical Workshop Contemporary Photon. Technol. Tech. Dig.*, 1998, pp. 227–228.

[66] F. Cecelja and W. Balachandran, "Optimized CdTe sensors for measurement of electric and magnetic fields in the near-field region," *IEEE Trans. Instrum. Meas.*, vol. 49, pp. 483–487, June 2000.

[67] N. Sahri and T. Nagatsuma, "Packaged photonic probes for an on-wafer broad-band millimeter-wave network analyzer," *Photon. Technol. Lett.*, vol. 12, pp. 1225–1227, Sept. 2000.

[68] S. Hunsche, D. M. Mittleman, M. Koch, and M. C. Nuss, "New dimensions in T-ray imaging," *IEICE Trans. Electron.*, vol. E81-C, pp. 269–275, 1998.

[69] Q. Chen, P. Y. Han, Z. Jiang, and X.-C. Zhang, "Recent development of free-space THz imaging," in *Proc. IEEE Int. Terahertz Electron. Conf.*, 1999, pp. 73–76.

[70] A. Sasaki and T. Nagatsuma, "Millimeter-wave imaging using an electrooptic detector as a harmonic mixer," *IEEE J. Select. Topics Quantum Electron.*, vol. 6, pp. 735–740, Sept.–Oct. 2000.

Tadao Nagatsuma (M'93) received the B.S., M.S., and Ph.D. degrees in electronic engineering from Kyushu University, Fukuoka, Japan, in 1981, 1983, and 1986, respectively.

In 1986, he joined the Atsugi Electrical Communications Laboratories, Nippon Telegraph and Telephone Corporation (NTT), Kanagawa, Japan. He is currently a Distinguished Technical Member, Senior Research Scientist, and Supervisor at the NTT Telecommunications Energy Laboratories, Kanagawa, Japan. His current research involves ultrahigh-speed electronics and millimeter-wave photonics, and their application to sensors and communications.

Dr. Nagatsuma is a member of the Optical Society of America, the Japan Society of Applied Physics, and the Institute of Electronics, Information and Communication Engineers (IEICE), Japan. He was the recipient of the 1989 Young Engineers Award presented by the IEICE, the 1992 IEEE Andrew R. Chi Best Paper Award, the 1997 Okochi Memorial Award, the 1998 Japan Microwave Prize, and the 2000 Minister's Award of the Science and Technology Agency.

Mitsuru Shinagawa (M'87) received the B.S. and M.S. degrees in electronic engineering from Tohoku University, Sendai, Japan, in 1983 and 1985, respectively.

In 1985, he joined the Electrical Communication Laboratories, Nippon Telegraph and Telephone Corporation (NTT), Tokyo, Japan. He is currently a Senior Research Engineer in the Department of Low-Energy Electronics Laboratory, NTT Telecommunications Energy Laboratories, Kanagawa, Japan. His technical areas of interest include electric-field measurement using laser-beam and high-precision measurements for ultrafast electronics.

Mr. Shinagawa is a member of the Institute of Electronics, Information and Communication Engineers (IEICE), Japan. He was the recipient of the 1992 Andrew R. Chi Prize Paper Award and the 1997 Okochi Memorial Award of Japan.

Nabil Sahri received the B.S. and M.S. degrees in physics, and Ph.D. degree in electrical engineering and device physics from the University of Paris 7-Denis Diderot, Paris, France, in 1990, 1992, and 1996, respectively.

From 1992 to 1996, he was with France Telecom-CNET Laboratories, Bagneux, France, initially as an Intern and then as a Contracted Researcher. From 1997 to 2000, he was a Post-Doctoral Fellow, and then a Senior Research Associate at the Nippon Telegraph and Telephone (NTT) Telecommunications Energy Laboratories (formerly System Electronics Laboratories), Atsugi, Japan, where he is engaged in research on millimeter-wave photonics and ultrafast measurement techniques. Since 2000, he has been with the Alcatel OPTO+ Corporate Research Center, Marcoussis Cedex, France, where he is involved with switching and routing subsystems.

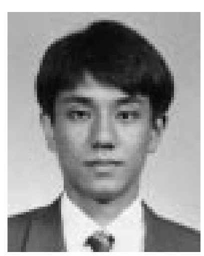
Dr. Sahri is a member of French Society of Physics. He was the recipient of the 1998 Japan Microwave Prize.

Ai-ichiro Sasaki was born on December 28, 1971, in Tokyo, Japan. He received the B.S. degree in applied physics from the Science University of Tokyo, Tokyo, Japan, in 1996, and the M.S. degree in physics from the University of Tokyo, Tokyo, Japan, in 1998.

In 1998, he joined the NTT Telecommunications Energy Laboratories, Kanagawa, Japan. His current research involves ultrafast optoelectronics and millimeter-wave photonics and their application.

Yakov Royter was born in Odessa (the former USSR). He received the B.S., M.S., and Ph.D. degrees from the Massachusetts Institute of Technology (MIT), Cambridge, in 1988, 1991, and 1997, respectively.

He was involved with optoelectronic device and dense integration technology development at MIT. From 1998 to 2001, he was with the NTT Laboratories, Atsugi, Japan, where he was engaged in research on wafer-bonded ultrahigh-speed photodetectors and the technology to enable their application in microwave photonic systems. Since 2001, he has been with HRL Laboratories, Malibu, CA, where he is involved with microelectronics.



Akihiko Hirata was born in Kyoto, Japan, on August 24, 1968. He received the B.S. and M.S. degrees in chemistry from Tokyo University, Tokyo, Japan, in 1992 and 1994, respectively.

In 1994, he joined the NTT Telecommunications Energy Laboratories (formerly the NTT LSI Laboratories), Kanagawa, Japan, where he has been engaged in the research of millimeter-wave antenna and photonic technology.

Mr. Hirata is a member of the Japan Society of Applied Physics.