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Photonic measurement technologies for high-speed electronics

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Abstract
In this paper we review recent advances in photonic measurement technologies for high-speed electronics covering the frequency range from gigahertz to terahertz. In the first part we describe the basic technologies for photonic measurement, i.e. the generation and detection of high-frequency electrical signals. In the second part, we discuss recent practical applications, including high-speed integrated circuit probers, sampling oscilloscopes, network analysers, and imaging systems.

Keywords: microwave measurement, millimetre-wave measurement, electro-optic measurement, time-domain measurement, optoelectronic devices, optical signal generation, semiconductor lasers, photodiode, fibre lasers, imaging, probe, network analyser

1. Introduction

Photonic technologies have recently been rapidly introduced to broadband communications systems, where terabit-class transmission is feasible with optical fibre cables. 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 regime [1], and some integrated circuits (ICs) are now 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 65 GHz (5 ps temporal resolution). For broadband vector network analysers it is 110 GHz. The latter can measure with instantaneous wide-band frequency sweeps from a few tens of megahertz to millimetre-wave frequencies.

To meet the above requirements in high-frequency measurement, purely-electronic approaches have made a steady progress, though technological difficulty increases more and more with higher frequencies [3–7]. As for the signal detection, Schottky diodes and their integrated functional form as a sampling gate or a mixer are used. The cut-off frequency of Schottky diodes now exceeds 20 THz, and a detection bandwidth of >1 THz can be obtained. On the other hand, the generation of electrical signals is a crucial issue [3]. Conventional continuous-wave (cw) electronic sources, such as Gunn diodes, impact avalanche transit-time (IMPATT) diodes and tunnel junction transit-time (TUNNETT) diodes, can generate fundamental power levels of >100 mW at 100 GHz, >10 mW at 200 GHz and 1 mW at 300 GHz. Quantum-well devices, such as resonant tunnelling diodes (RTD) and superlattice electronic devices, are promising, but their power obtained to date is relatively low (<1 mW). Harmonic frequency multiplication by nonlinear devices such as heterostructure varactors (HBV) is used to achieve higher power at 200–300 GHz. Generating >300 GHz broadband signals is currently a greater challenge than detecting such signals.

Electrical pulses with a pulse width of <5 ps or with a rise/fall time of <1 ps can be generated with the use of nonlinear transmission line (NLTL) circuits [4]. By combining the NLTL pulse generator and the Schottky diode sampler, an electrical signal sampling circuit with a bandwidth of 725 GHz [5] and network analysers that operate across the 7–200 GHz [6] and 70–230 GHz [7] bands have been reported. Millimetre-wave monolithically integrated circuit (MMIC) technology is the key to achieving the broadband operation of these instruments. Waveguide-based and/or quasi-optical systems offer higher-frequency operation at up to 1 THz, although with a discontinuous bandwidth [8].

In order to overcome several technological limitations on electronic approaches, there has been increasing interest in photonic techniques. The emergence of femtosecond

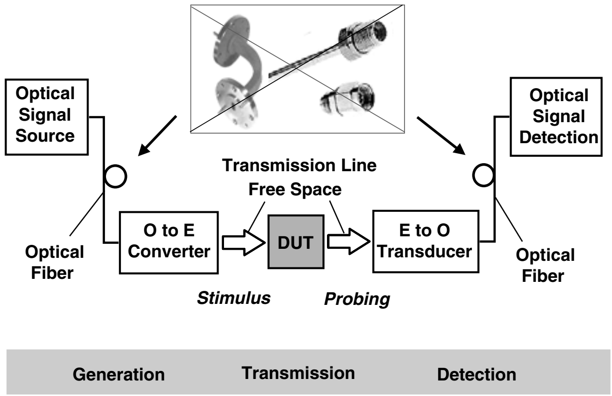


Figure 1. Concept of photonic measurement for electronic devices and systems.

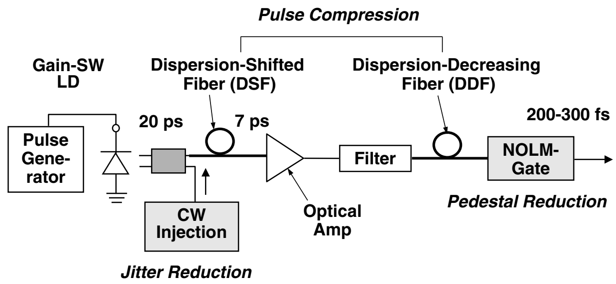


Figure 2. Block diagram of the repetition-rate variable optical pulse generation with jitter and pedestal reduction schemes.

and picosecond pulse lasers spawned a variety of photonic measurement techniques for high-speed electronics in the 1980s [9, 10]. Those lasers, however, were bulky dye or Nd:YAG lasers and their handling required special skills, so their application to measurement was the preserve of optical engineers and of physicists studying ultrafast phenomena. In the 1990s, with the development of easy-to-use Ti:sapphire lasers, semiconductor diode lasers, fibre lasers, and other photonic components such as detectors, modulators and amplifiers, photonic measurement techniques made remarkable progress, becoming accessible to a broader range of people including electrical engineers and circuit designers.

In this paper we describe the recent progress in photonic measurement technologies for high-speed electronics, which cover the frequency range from gigahertz to terahertz. Firstly, the basic technologies used in measurement, namely the optical generation and detection of high-speed electrical signals, are described. This is followed by a description of the application of these techniques to contemporary IC testers, sampling oscilloscopes, network analysers and millimetre-wave imaging systems.

2. Basic technologies for photonic measurement

The basic idea of a photonic measurement system is shown in figure 1 [11, 12]. An optical-to-electrical (O-E) converter generates electrical signals, which are transmitted, as a stimulus, through free space or a transmission line 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 co-axial cables and bulky, metallic hollow waveguides for delivering and receiving high-frequency electrical signals are replaced with optical fibre cables.

2.1. 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 with fibres has given us femtosecond lasers that provide turn-key and maintenance-free operation. The most promising technologies for pulse sources are a gain-switched laser diode [13] and a mode-locked fibre laser [14], both of which are used with a fibre-optic pulse compressor to reduce the pulse width down to the desired duration. 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 the sampling measurement 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 (figure 2). 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 fibres, pedestals often arise 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 MLLD with optical injection [19–21]. With either scheme, >100 GHz signals with sub-harmonic 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 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 line widths. The combination of a fibre 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 which 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].

2.2. Photonic generation of electrical stimulus signals

Electrical signals as a stimulus are generated by converting sinusoidal or pulsed optical signals to electrical signals, and

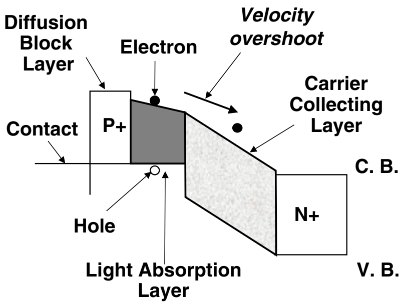


Figure 3. Structure of the UTC-PD.

they are delivered to the DUT via an antenna or transmission line. As for the O-E converters, photoconductors and photodiodes have been used.

Low-temperature-grown (LT) GaAs is a widely used photoconductive (PC) material for pulse and sinusoidal signal generation at a laser wavelength of <800 nm [25, 26]. At 1.3–1.55 μm wavelength, where the loss and dispersion of fibres are minimal, both the bandwidth and the output power level of PIN photodiodes have recently been greatly improved through the use of waveguide, travelling-wave and distributed structures [27,28], and novel carrier dynamics [29]. Of these, a uni-travelling carrier photodiode (UTC-PD) [29, 30] 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 (figure 3). The smallest pulse width obtained to date is 0.97 ps, and this corresponds to a 3 dB bandwidth of 310 GHz [31]. Using a UTC-PD and an MLLD, a 100 GHz cw with an output power of 11 dB m has been obtained [32]. This is comparable to the performance of solid-state electronic devices.

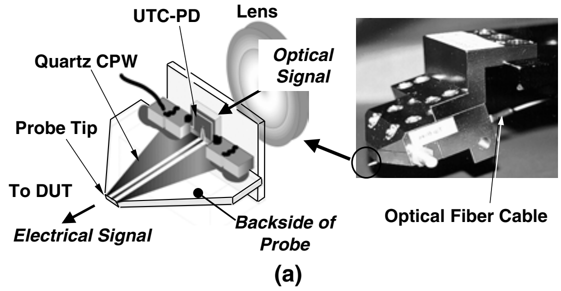
Figure 4 shows two examples of fibre-optic electrical signal generators that employ UTC-PDs. In figure 4(a), an O-E conversion probe head for triggering electronic devices and ICs on wafer is formed by bonding the UTC-PD to a coplanar waveguide made on a quartz substrate [33]. The 3 dB bandwidth of the probe is >100 GHz. The peak output voltage is 900 mV, which is high enough to directly drive digital ICs.

A free-space millimetre-wave emitter [34,35] for wireless applications is shown in figure 4(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 millimetre-wave signals in the direction opposite to the illumination. At 120 GHz, >5 mW was generated in the PD chip and >3 mW was emitted into free space.

Moreover, the monolithic integration of PDs with antennas on the same substrate has been successfully demonstrated. By eliminating the process of bonding the components, this approach improves ease of manufacture and performance [36–38]. Yagi-Uda and patch antennas have been monolithically integrated with the UTC-PD on InP and Si substrates, respectively [37, 38].

2.3. Photonic probing of electrical signals

In probing applications, the electrical signal is detected by an electrical-to-optical transducer in combination with an optical signal source. Table 1 summarizes several optical probing techniques. Signal detection techniques are based on the interaction between optical and electrical signals. The physical phenomenon involved can be an electro-optic (EO) effect [39], a PC effect [40], an electro-absorption (EA) effect [41], or a magneto-optic (MO) effect [42, 43].



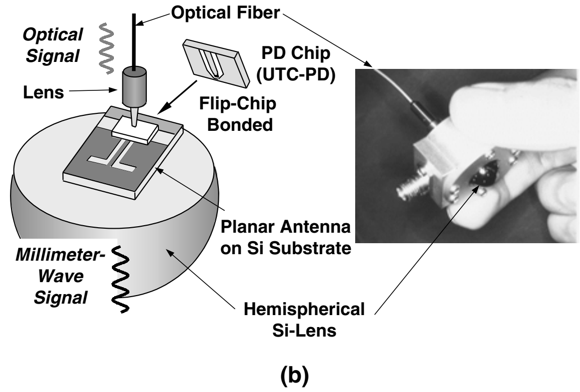


Figure 4. Two microwave signal generators based on photonic techniques. (a) O-E probe head for testing electronic devices on wafer. (b) Millimetre-wave signal emitter for free-space applications.

Table 1. Optical probing techniques and their physical basis.

Method	Physical basis
Electro-optic (EO) probing	Change in refractive index due to electric field
Photoconductive (PC) probing	Change in conductivity due to photon
Electro-absorption (EA) probing	Change in absorption due to electric field
Magneto-optic (MO) probing	Polarization rotation of the incident beam due to magnetic field

Among these, optical sampling on the basis of an EO effect, or EO probing, has become the most common in various types of measurement tool and instrumentation because it has the highest temporal resolution and is easy to use at long optical wavelengths. Figure 5 shows the typical configurations for the EO measurement of electrical signals propagating on transmission lines in ICs or printed circuit boards and signals being radiated from antennas. 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 sub-micrometre spatial resolution. However, when bandwidths of >100 GHz must be handled,

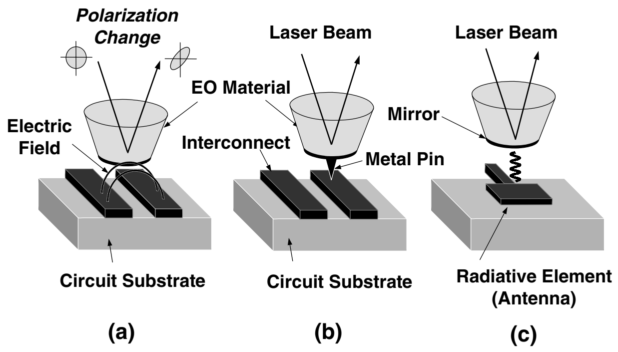


Figure 5. Typical configurations for device measurement based on EO probing.

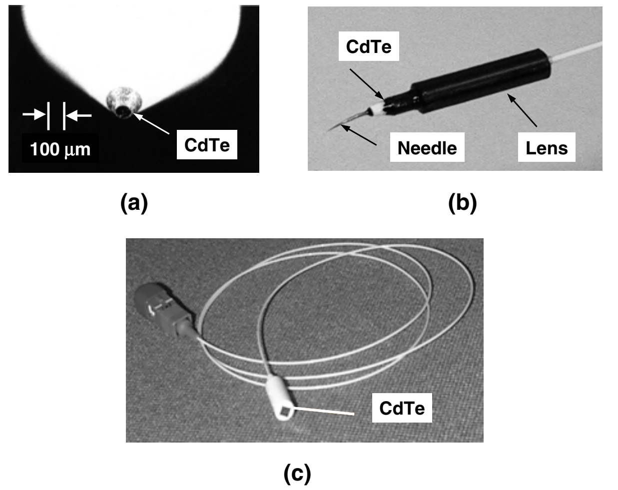


Figure 6. EO sensor heads for (a), (b) IC probing and (c) free space.

the fringing electric field is sensed without using the metal tip.

Figure 6 shows examples of actual sensors made of CdTe crystals: an EO probe tip used for non-contact internal IC testing ((100)-cut crystal) [44], an EO probe with a needle tip for LSI testing [45], and a fibre-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 [46] 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 and sensitivity.

3. Practical instrumentation

Using the above basic technologies, different photonic instruments for each developmental level in electronics have been realized: a network analyser for transistors, an IC prober for IC chips, and a hand-held-type high-impedance probe for printed circuit boards. All these instruments have bandwidths that surpass those of conventional ones as shown in table 2.

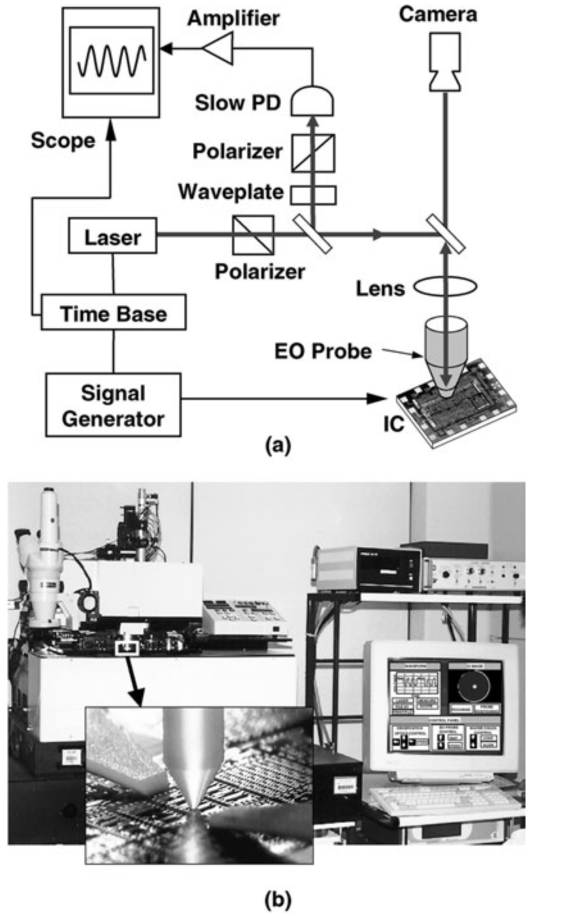


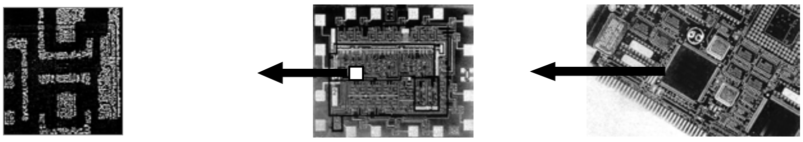
Figure 7. (a) Typical configurations for measuring internal-node voltage waveforms in ICs based on EO probing.
(b) Fully-automated IC testing system.

3.1. IC testing system

The most common 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 [44, 47–49]. Figures 7(a) and (b) show a typical configuration for measuring internal-node voltage waveforms in ICs on the basis of EO sampling, and photographs of the IC prober at work [50]. Examples of waveforms measured from a communications IC operating at 20 Gb s^{-1}, and from an ultrafast photodiode are shown in figures 8(a) and (b), respectively. Minimum detectable voltages in such applications are typically 1 mV.

In addition to the features 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 development is the combination with scanning probe microscopy that offers extremely fine spatial resolution (<100 nm resolution) [51]. This form of EO probing has been applied to CMOS-based ULSIs of the current generation, i.e. with sub-micrometre linewidth. To access the lowest-level conductors in LSIs with multi-level interconnections, a focused ion beam was used to make tungsten via-holes and pads especially for EO probing [52]. The other new feature is two-dimensional field mapping [53,54]. A photonic

Table 2. Developed photonic instruments for electronics.

DUTs			
	Transistor	IC chip	Circuit board
Instruments	Network analyser (GHz)	IC prober (GHz)	High-impedance probe (GHz)
Photonic	>300	>1000	>10
Conventional	110	5	2.5

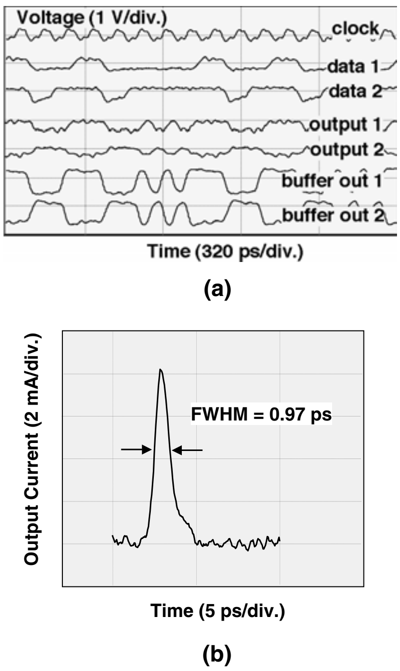


Figure 8. Examples of measured temporal waveforms for (a) communications IC, and (b) photo-response of the photodiode.

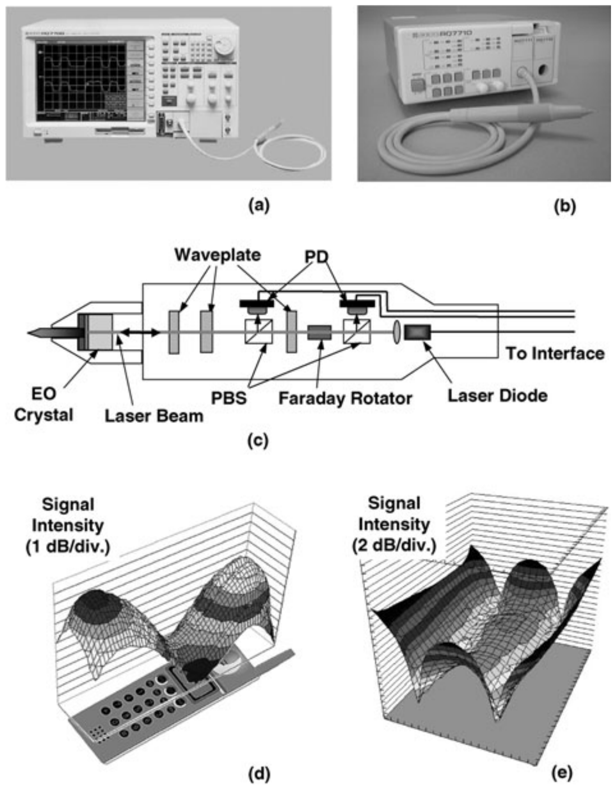


Figure 9. Two types of hand-held high-impedance probe. (a) EO digital sampling oscilloscope. (b) Real-time EO probe unit. (c) Block diagram of the typical probe head. Distribution of the electric field radiating from (d) cellular phone and (e) printed circuit board.

field-probing technique is less invasive than inductive probing and makes higher spatial resolutions possible. It could thus 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 method, and the finite-difference time-domain (FDTD) method.

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 (figure 4(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 [55, 56].

3.2. Hand-held high-impedance probes

Figure 9 shows a hand-held probe for circuit board and module measurement. All of the photonic components required for EO probing are integrated into the probe [57, 58]. Two types of probe have been developed. One is a sampling oscilloscope using a pulse laser (figure 9(a)) [57], and the other is a real-time probe unit with a cw laser (figure 9(b)) [58]. The latter unit is employed with a conventional electronic sampling oscilloscope or a spectrum analyser. The unique features of these probes are a larger bandwidth, a higher input impedance, single-contact, i.e. no ground-contact operation, and high degree of immunity to electrostatic discharge.

One of the most recent applications of the probe is 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 distributions for a cellular phone with a call in progress, and for a printed circuit board resonating at 710 MHz are shown in figures 9(d) and (e), respectively. Similar techniques have led to the successful measurement of the two-dimensional radiation field from planar antennas [59, 60]. Several types of optical sensor for measuring electric fields as well as magnetic fields have been developed with practical design and features [43, 61, 62].

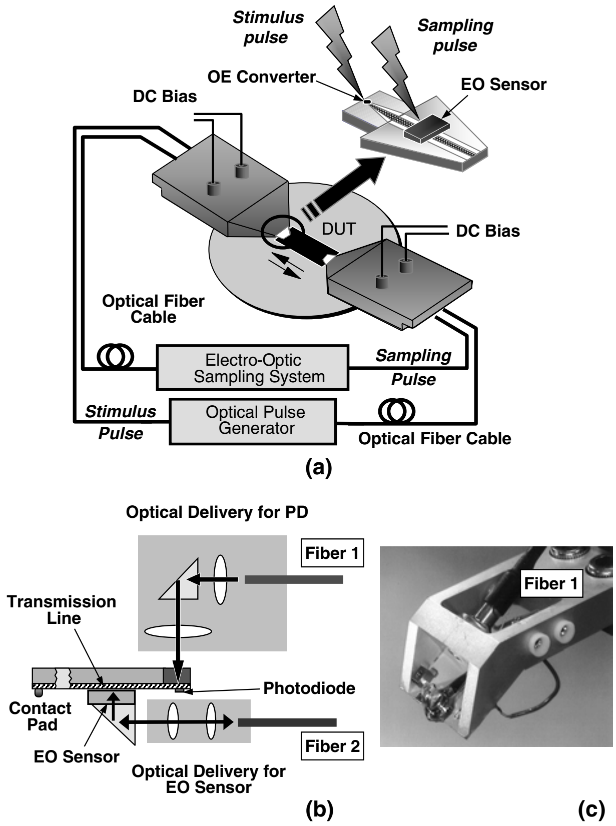


Figure 10. Photonic millimetre-wave network analyser. (a) System configuration. (b) Optical arrangement for generating stimulus signal and for detecting electrical response. (c) Photograph of the integrated probe head.

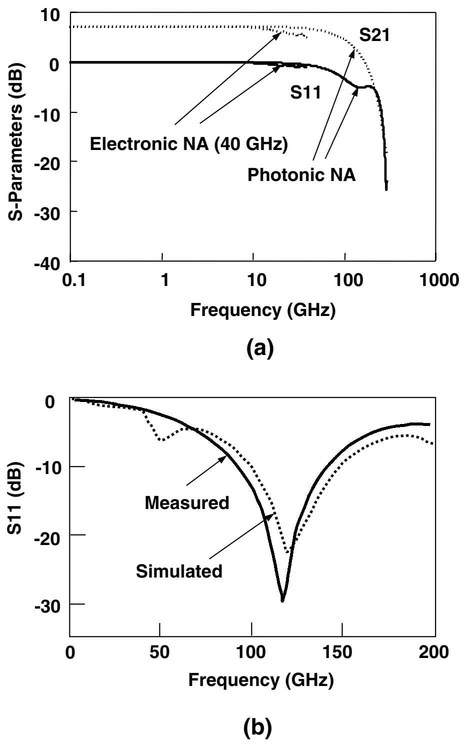


Figure 11. Examples of measured frequency characteristics for (a) HEMT and (b) antenna.

3.3. Vector network analysers

There is now an urgent need for a millimetre-wave broadband network analyser, since the upper frequencies of conventional vector network analysers are limited to 110 GHz for full-band operation (continuously from a few tens of megahertz to millimetre-wave frequencies), and they can only operate in the linear or small signal regime. This frequency limit can be extended to upper millimetre-wave [63] and sub-millimetre-wave frequencies [64], 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 millimetre-wave network analyser that enables a full-band measurement only with a single set-up. Figure 10(a) illustrates the head of the ultra-broadband network analyser, 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, 65]. 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 figure 1.

An effective measurement bandwidth of >300 GHz was obtained and the system was used to characterize >100 GHz HEMTs with excellent reproducibility of measurement, as is shown in figure 11(a). Data obtained with a conventional 40 GHz network analyser are shown for comparison. The results agree quite well. S11 for the antenna was measured as shown in figure 11(b). This antenna is a slot antenna used for the photonic millimetre-wave emitter (figure 4(b)). A simulation based on the FDTD analysis and the measured data are in good agreement. The dynamic range of the current photonic network analyser is >30 dB up to 100 GHz and >20 dB to 200 GHz. Additional work is under way to enhance the accuracy of the system by increasing the sensitivity or the dynamic range and by using proper calibration.

3.4. Imaging systems

Imaging using electromagnetic waves in the millimetre to sub-millimetre wavelength range is useful in obtaining information, for example, through clouds, fog, smoke, dust and other screening conditions, for which visible, IR and x-ray systems are ineffective. The imaging system using photonically generated pulsed or single-cycle electromagnetic waves with a sub-picosecond duration has recently been extensively studied [66, 67]. 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 biological imaging. This covers a wide range of fields, including science, biomedicine, industry, electronics and quality control.

Figure 12 shows another type of photonic imaging system in which cw millimetre waves are applied. The millimetre-wave signal reflected by the object is detected with the waveguide-mounted EO sensor head [68]. The minimum detectable power of the sensor is less than -60 dB m. The object shown in figure 12(b) is a 5 mm thick slice of pork.

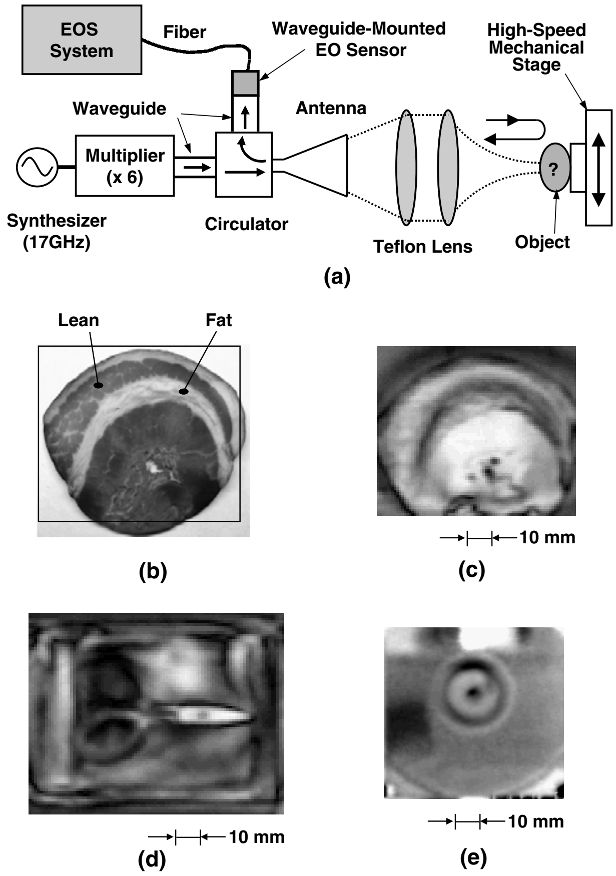


Figure 12. Reflection-type millimetre-wave imaging system. (a) System configuration. (b) Visible image of a slice of pork. Obtained millimetre-wave images of (c) slice of pork, (d) clipper in a purse and (e) floppy disk.

We managed to obtain an image of the object at 100 GHz. It is important that images with visible light and millimetre waves are rather different. In contrast to the visible light case, the millimetre-wave signal is absorbed much more by the lean than by the fatty portion (figure 12(c)). Figures 12(d) and (e) are images of a small clipper in a purse and a floppy disk, respectively. We thus get a good view of them with a diffraction-limited resolution of about 3 mm. The acquisition time for 20 000 pixel amplitude and phase images is $<$10 min, which is limited by the speed of the motor-driven translation stage. Transmission-type imaging has also been demonstrated [69].

As described in section 2, a photonic approach could lead to making frequency-variable millimetre-wave sources. In the future, the combination of such frequency-variable sources and EO-based broadband detection may enable us to obtain a millimetre-wave spectroscopic or millimetre-wave *colour* images.

4. Conclusions

We have reviewed recent progress in photonic instrumentation and measurement for ultrafast electronics. Progress has been accelerated in recent years, in particular, by the use of 1.55 μm semiconductor lasers, detectors, amplifiers and fibre-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 1 to 300 GHz, and will allow us to reach the terahertz range in the near future.

The use of photonic technologies for electrical signal measurement 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 more costly 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.

Finally, we can expect cooperation of electronic and photonic technologies to further lead to exciting new applications not only in telecommunications and related fields but also in environmental and biological sensing.

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References

[1] Rodwell M J W, Lee Q, Mensa D, Guthrie J, Bester Y, Martin S and Smith R P 1999 Heterojunction bipolar transistors with greater than 1 THz extrapolated power-gain cutoff frequencies *Proc. IEEE Int. Conf. on Terahertz Electronics* pp 120–3

[2] Otsuji T 2000 Present and future of high-speed electronic devices and IC's *MWE 2000 Microwave Workshop Dig.* pp 237–42

[3] Eisele H 1999 Two-terminal devices as fundamental solid-state terahertz oscillators *EUROOPTO Conf. on Terahertz Spectroscopy and Applications Proc. SPIE* **3828** 70–80

[4] Rodwell M J W *et al* 1994 Active and nonlinear wave propagation devices in ultrafast electronics and optoelectronics *Proc. IEEE* **82** 1037–59

[5] Bhattacharya U, Allen S T and Rodwell M J W 1995 DC-725 GHz sampling circuits and subpicosecond nonlinear transmission lines using elevated coplanar waveguide *IEEE Microw. Guid. Wave Lett.* **5** 50–2

[6] Yu R Y, Reddy M, Pusl J, Allen S T, Case M and Rodwell M J W 1995 Millimetre-wave on-wafer waveform and network measurements using active probes *IEEE Trans. Microw. Theory Tech.* **43** 721–9

[7] Wohlgemuth O, Rodwell M J W, Reuter R, Braunstein J and Schlechtweg M 1999 Active probes for network analysis within 70–230 GHz *IEEE Trans. Microw. Theory Tech.* **47** 2591–8

[8] Goldsmith P F 1998 Quasioptical systems Gaussian beam quasioptical propagation and applications (Piscataway, NJ: IEEE)

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

[10] Marcus R B (ed) 1990 Measurement of high-speed signals in solid-state devices *Semiconductors and Semimetals* vol 28 (San Diego, CA: Academic)

[11] Nagatsuma T, Sahri N, Yaita M, Ishibashi T, Shimizu N and Sato K 1998 All optoelectronic generation and detection of millimetre-wave signals *Tech. Dig. Microw. Photonics* 5–8

[12] Nagatsuma T, Shinagawa M, Sahri N, Sasaki A, Royter Y and Hirata A 2001 1.55 μm photonic systems for microwave and millimetre-wave measurement *IEEE Trans. Microw. Theory Tech.* **49** 1831–9
[13] Sahri N, Nagatsuma T, Yaita M and Shimizu N 1998 Picosecond synchronous electro-optic sampling with a jitter-reduced gain-switched laser diode *Japan. J. Appl. Phys.* **37** L39–41
[14] Sahri N and Nagatsuma T 1999 Application of 1.55 μm photonic technologies to practical millimetre-wave network analyzer *IEICE Trans. Electron.* **82C** 1307–11
[15] Yaita M and Nagatsuma T 1998 The effect of sampling-pulse pedestals on temporal resolution in electro-optic sampling *IEICE Trans. Electron.* **81C** 254–9
[16] Tamura K R and Nakazawa M 1999 Spectral-smoothing and pedestal reduction of wavelength tunable quasi-adiabatically compressed femtosecond solitons using a dispersion-flatted dispersion-imbalanced loop mirror *IEEE Photonics Technol. Lett.* **11** 230–2
[17] Sato K, Kotaka I, Kondo Y and Yamamoto M 1996 Active mode locking at 50 GHz repetition frequency by half-frequency modulation of monolithic semiconductor lasers integrated with electroabsorption modulators *Appl. Phys. Lett.* **69** 2626–8
[18] Sato K, Kotaka I, Hirano A, Asobe M, Miyamoto Y, Shimizu N and Hagimoto K 1998 High-repetition frequency pulse generation at 102 GHz using mode-locked lasers integrated with electroabsorption modulators *Electron. Lett.* **34** 790–2
[19] Arahira S, Matsui Y and Ogawa Y 1996 Mode-locking at very high repetition rates more than terahertz in passively mode-locked distributed-Bragg reflector laser diodes *IEEE J. Quantum Electron.* **32** 1211–14
[20] Arahira S, Katoh Y, Kunimatsu D and Ogawa Y 2000 Stabilization and timing jitter reduction of 160 GHz colliding-pulse mode-locked laser diode by subharmonic-frequency optical pulse injection *IEICE Trans. Electron.* **83C** 966–73
[21] Wen Y J, Novak D, Liu H F and Nirmalathas A 2001 Generation of 140 GHz optical pulses with suppressed amplitude modulation by subharmonic synchronous mode-locking of Fabry–Perot semiconductor *Electron. Lett.* **37** 581–2
[22] Payne J, Shillue B and Vaccari A 1999 Photonic techniques for use on the Atacama large millimetre array *Techn. Dig. Microw. Photonics* 105–8
[23] Swanson E A, Chinn S R, Hall K, Rauschenbach K A, Bondurant R S and Miller J W 1994 100 GHz soliton pulse train generation using soliton compression of two phase side bands from a single DFB laser *IEEE Photonics Technol. Lett.* **6** 1194–6
[24] Gough O P, Silvia C F C and Seeds A J 1999 Exact millimetre-wave frequency synthesis by injection locked laser comb line selection *Techn. Dig. Microw. Photonics* 61–4
[25] Verghese S, McIntosh K A and Brwon E R 1997 Optical and terahertz power limits in the low-temperature-grown GaAs photomixer *Appl. Phys. Lett.* **71** 2743–5
[26] Matsuura S, Blake G A, Wyss R A, Pearson J C, Kadow C, Jackson A W and Gossard A C 1999 A travelling-wave THz photomixer based on angle-tuned phase matching *Appl. Phys. Lett.* **74** 2872–4
[27] Stöhr A, Heinzekmann R, Kaczmarek C and Jäger D 2000 Ultra-broadband Ka to W-band 1.55 μm travelling-wave photomixers *Electron. Lett.* **36** 970–1
[28] Chau T, Kaneda N, Jung T, Rollinger A, Mathai S, Qian Y, Itoh T, Wu M C, Shillue W P and Payne J M 2000 Generation of millimetre waves by photomixing at 1.55 μm using InGaAs–InAlAs–InP velocity-matched distributed photodetectors *IEEE Photonics Technol. Lett.* **12** 1055–7
[29] Ishibashi T, Shimizu N, Kodama S, Ito H, Nagatsuma T and Furuta T 1997 Uni-travelling-carrier photodiodes *Technical Digest Ultrafast Electronics and Optoelectronics* pp 83–7
[30] Ishibashi T, Furuta T, Fushimi H, Kodama S, Ito H, Nagatsuma T, Shimizu N and Miyamoto Y 2000 InP/InGaAs uni-travelling-carrier photodiodes *IEICE Trans. Electron.* **83C** 938–49
[31] Ito H, Furuta T, Kodama S and Ishibashi T 2000 InP/InGaAs uni-travelling-carrier photodiode with 310 GHz bandwidth *Electron. Lett.* **36** 1809–10
[32] Nagatsuma T, Ishibashi T, Hirata A, Hirota A, Minotani T, Sasaki A and Ito H 2001 Characterization of uni-travelling-carrier-photodiode monolithically integrated with matching circuit *Electron. Lett.* **37** 1246–7
[33] Otsuji T, Sahri N, Shimizu N, Nagatsuma T and Ishibashi T 1999 A 105 GHz bandwidth optical-to-electrical conversion stimulus probe head employing a uni-travelling-carrier photodiode *IEEE Photonics Technol. Lett.* **11** 1033–5
[34] Nagatsuma T, Hirata A, Royter Y, Shinagawa M, Furuta T, Ishibashi T and Ito H 2000 A 120 GHz integrated photonic transmitter *Techn. Dig. Microw. Photonics* 225–8
[35] Hirata A, Ishii H and Nagatsuma T 2001 Design and characterization of a 120 GHz millimetre-wave antenna for integrated photonic transmitters *IEEE Trans. Microw. Theory Tech.* **49** 2157–62
[36] Royter Y, Minotani T, Ishii H, Hirata A, Yagi S, Machida K, Furuta T, Ishibashi T, Sasaki A and Nagatsuma T 2000 Ultrahigh-speed 1.55 μm photodiodes on Si with low-loss millimetre-wave waveguides *Tech. Dig. IEEE LEOS* pp 283–4
[37] Minotani T, Royter Y, Ishii H, Hirata A, Machida K, Sasaki A and Nagatsuma T 2001 Three-dimensional millimetre-wave photonic integrated circuits on Si *Technical Digest IEEE MTT-S Int. Microwave Symp.* pp 57–60
[38] Hirata A, Furuta T and Nagatsuma T 2001 Monolithically integrated Yagi-Uda antenna for photonic emitter operating at 120 GHz *Electron. Lett.* **37** 1107–9
[39] Valdmanis J A, Mourou G and Gabel C W 1983 Subpicosecond electro-optic sampling *IEEE J. Quantum Electron.* **19** 664–7
[40] Auston D H 1975 Picosecond optoelectronic switching and gating in silicon *Appl. Phys. Lett.* **26** 101–3
[41] Nagatsuma T, Yaita M and Iwatsuki K 1997 Optical signal measurement using electro-absorption sampling *Technical Digest Ultrafast Electronics and Optoelectronics* pp 172–4
[42] Riordan J A, Sun F G, Lu Z G and Zhang X C 1997 Free-space transient magneto-optic sampling *Appl. Phys. Lett.* **71** 1452–4
[43] Wakana S, Ohara T, Abe M, Yamazaki E, Kishi M and Tsuchiya M 2000 Fiber-edge electrooptic/magnetooptic probe for spectral-domain analysis of electromagnetic field *IEEE Trans. Microw. Theory Tech.* **48** 2611–6
[44] Nagatsuma T 1996 Electro-optic testing technology for high-speed LSIs *IEICE Trans. Electron.* **79C** 482–8
[45] Shinagawa M and Hashimoto C 2001 An electro-optic microprobe for internal-node waveform measurement on LSIs *Technical Digest LSI Testing Symp.* pp 115–20
[46] Chu Z H, Pan C L, Lo Y H, Wu M C, Wang S, Kolner B H and Wang S Y 1987 Electro-optic measurement of standing waves in a GaAs coplanar waveguide *Appl. Phys. Lett.* **50** 1228–30
[47] Nagatsuma T 1993 Measurement of high-speed devices and integrated circuits using electro-optic sampling techniques *IEICE Trans. Electron.* **76C** 55–63
[48] Nagatsuma T (ed) 1996 Special issue on probing of ultrafast devices and integrated circuits *Opt. Quantum Electron.* **28**
[49] Pfeifer T, Heiliger H M, Löffler T, Ohlhoff C, Meyer C, Lüpke G, Roskos H G and Kurz H 1996 Optoelectronic on-chip characterization of ultrafast electronic devices: measurement techniques and applications *IEEE J. Sel. Top. Quantum Electron.* **2** 586–604
[50] Shinagawa M and Nagatsuma T 1994 An automated electro-optic probing system for ultrahigh-speed ICs *IEEE Trans. Instrum. Meas.* **43** 843–7
[51] Ozaki K, Sekiguchi H, Wakana S, Goto Y, Umehara Y and

Matsumoto J 1996 Novel optical probing system with submicron spatial resolution for internal diagnosis of VLSI circuits *Proc. Int. Test Conf.* pp 269–75
[52] Hashimoto C, Takizawa T, Nakajima S, Shinagawa M and Nagatsuma T 2001 Observation of the internal waveforms in high-speed high-density LSIs using an EOS prober *Microelectron. Reliab.* **41** 1203–9
[53] David G, Tempel R, Wolff I and Jäger D 1996 Analysis of microwave propagation effects using 2D electro-optic field mapping techniques *Opt. Quantum Electron.* **28** 919–31
[54] Yang K, David G, Robertson S V, Whitaker J F and Katehi L P B 1998 Electrooptic mapping of near-field distributions in integrated microwave circuits *IEEE Trans. Microw. Theory Tech.* **46** 2338–43
[55] Otsuji T, Nagatsuma T, Kato K and Yoneyama M 1996 Widely tunable electrooptic pulse-pattern generation and its application to on-wafer large-signal characterization of ultrahigh-speed electronic devices *Opt. Quantum Electron.* **28** 991–1005
[56] Otsuji T, Kato K, Kimura S and Nagatsuma T 1999 Wide-band high-efficiency optical-to-electrical conversion stimulus probe heads for testing large-signal response of high-speed electronic devices *IEEE Trans. Microw. Theory Tech.* **47** 525–33
[57] Shinagawa M and Nagatsuma T 1996 A novel high-impedance probe for multi-gigahertz signal measurement *IEEE Trans. Instrum. Meas.* **45** 575–9
[58] Shinagawa M, Nagatsuma T, Ohno K and Jin Y 2001 A real-time electro-optic handy probe using a CW laser *IEEE Trans. Instrum. Meas.* **50** 1076–80
[59] Imaizumi Y, Shinagawa M and Ogawa H 1995 Electric field distribution measurement of microstrip antennas and arrays using electro-optic sampling *IEEE Trans. Microw. Theory Tech.* **43** 2402–7
[60] Yang K, Katehi L P B and Whitaker J F 2000 Electro-optic field mapping system utilizing external gallium-arsenide probes *Appl. Phys. Lett.* **77** 486–8
[61] Stöhr A, Heinzekmann R, Alder T, Kalinowsli D, Gross M and Jäger D 1998 Integrated optical E-field sensors using TW EA-modulators *Technical Digest Int. Topical Workshop on Contemporary Photonic Technologies* pp 227–8
[62] Cecelja F and Balachandran W 2000 Optimized CdTe sensors for measurement of electric and magnetic fields in the near-field region *IEEE Trans. Instrum. Meas.* **49** 483–7
[63] Oleson Microwave Labs Model V05VNA-T/R (140–220 GHz) (Morgan Hill, CA)
[64] AB Millimetre Model MVNA 8-350 with options ESA Paris, France
[65] Sahri N and Nagatsuma T 2000 Packaged photonic probes for an on-wafer broad-band millimetre-wave network analyzer *Photonics Technol. Lett.* **12** 1225–7
[66] Hunsche S, Mittleman D M, Koch M and Nuss M C 1998 New dimensions in T-ray imaging *IEICE Trans. Electron.* **81C** 269–75
[67] Chen Q, Han P Y, Jiang Z and Zhang X C 1999 Recent development of free-space THz imaging *Proc. IEEE Int. Conf. on Terahertz Electronics* pp 73–6
[68] Sasaki A and Nagatsuma T 2002 Reflection-type millimetre-wave imaging with a high-sensitivity waveguide-mounted electro-optic sensor *Japan. J. Appl. Phys.* **41** L83–6
[69] Sasaki A and Nagatsuma T 2000 Millimetre-wave imaging using an electro-optic detector as a harmonic mixer *IEEE J. Sel. Top. Quantum Electron.* **6** 735–40