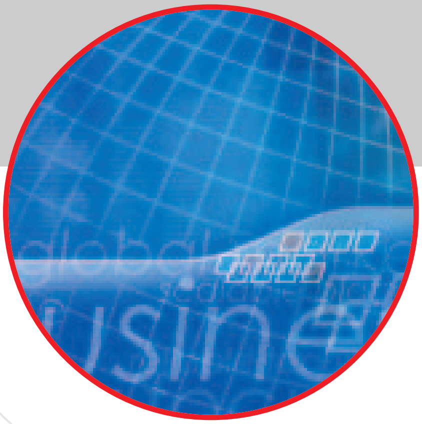


Photonic techniques for the generation and detection of millimeter waves and their applications

S. Donati, T. Tambosso

ABSTRACT - IN THIS PAPER A REVIEW OF THE RECENTLY DEVELOPED PHOTONIC TECHNIQUES FOR THE GENERATION (PHOTOMIXING, ACTIVE AND PASSIVE MODE-LOCKING) AND DETECTION OF MILLIMETER WAVES IS PRESENTED; THE RESULTS ARE COMPARED WITH THE ONES OBTAINED BY CONVENTIONAL ELECTRONIC TECHNIQUES.

WE WILL THEN REPORT ON THE MAIN APPLICATIONS OF MM-WAVES IN THE AREAS OF COMMUNICATIONS (MM-WAVE WLAN, RADIO OVER FIBER, 4G MOBILE BROADBAND SYSTEMS). ALSO A SHORT MENTION WILL BE MADE OF APPLICATIONS IN RADIO-ASTRONOMY (MM-WAVE DETECTORS) AND BIO-ENGINEERING (TERAHERTZ IMAGING).

INTRODUCTION

In scientific literature we have recently seen a considerable increase in activities related to microwave photonics. Until a few years ago, despite new scientific journals where the term optics (or photonics) was associated with microwave, basically no technical innovations were to be noted, apart from a race for higher and higher frequencies, culminating in the field of microwaves, handled or transmitted by photonic systems.

However, at least two highly significant breakthroughs have been achieved, both reaching beyond the purely electronic traditional technique through the decisive contribution of photonics.

The two examples, which will be briefly commented upon, are: the photodiode with integrated optical pre-amplifier, and the generation of mm-wave signals by photomixing.

The first example (1,2) is based on the integration, on the same semiconductor substrate, of the photodetector and optical pre-amplifier. This possibility was by no means novel, being also described in textbooks (3), however, its scientific importance is given by the fact that, for the first time, 40Gb/s systems reach beyond the purely electronic solution provided by transimpedance amplifiers (front-end), replacing it with an optical pre-amplifier and obtaining improved noise performance (3). Additionally, if we consider that the evolution of bit rate is not over, and the next step after 40Gb/s is expected to be 160Gb/s (already a topic of discussion, although for the time being only to evaluate its potential (4)), it is clear that the technical solution for the receiver will undoubtedly incorporate the still new approach consisting of an optical pre-amplifier integrated with a photodiode.

This solution is technically superior to the traditional ones, based – as known – on internal gain mechanisms (avalanche photodiode APD) associated with the transimpedance pre-amplifier. As the bit rate increases, the photodetector requires a

T. Tambosso

tiziana.tambosso@telecomitalia.it

Tiziana Tambosso received the M.S. and Ph.D. degrees in optoelectronic engineering from University of Pavia, Italy, in 1983 and 1988 respectively. After a period spent with SGS-Thomson, working on design and development of bipolar electronic circuits for telecommunication applications, she has been a researcher at University of Pavia giving contributions in optoelectronics (all-fiber passive components, fiber optic sensors). From 1989 to 1993 she has been responsible for the fiber optic devices group at SIRTI, R&D Division, developing optical fiber couplers, attenuators and fiber optic amplifiers. In 1993 she joined CSELT (now TILAB), the Telecom Italia Group R&D laboratories, where, as head of a research group and project leader, she has been working on second window fiber optic amplifiers, optical fibers, passive optical components, optoelectonics devices for millimeter waves generation and MEMS for e-tag.

From 1993 to 1997 Dr. Tambosso has contributed to IEC standard activity as Secretary of Subcommittee SC86B on fiber optic interconnecting devices and passive components. She has authored or coauthored about 50 papers in Journals or Conference Proceedings, and holds 8 patents. She has promoted, as chairperson of the Technical Programme Committee, two editions of WFOPC, the International Workshop on Fiber Optic Passive Components of IEEE-LEOS. She has served as Guest Editor of the IEEE Selected Topics in Quantum Electronics of Sept. 1999 on Fiber Optic Passive Components. She was engaged in the Technical Programme Committee of the OFC (Optical Fiber Communication Conference) for three years, and presently, she is member of ECOC 2003 (European Conference on Optical Communication) Technical Programme Committee.

Dr. Tambosso is a member of AEI, senior member of IEEE and Chairperson of IEEE LEOS Italian Chapter.

progressively smaller termination resistance, as load of the transimpedance amplifier, to maintain the bandwidth (though with some recovery due to the reduced junction capacity resulting from a decreased surface area). However, impedance values typical of transmission lines (≈50 ohm) are reached, which makes the transimpedance amplifier meaningless. Moreover, the avalanche multiplication cannot be fully used, because of the unavailability of a semiconductor (either standard or based on bandgap engineering) with a high ionization coefficient ratio (for gain) and high carrier mobility (for bandwidth).

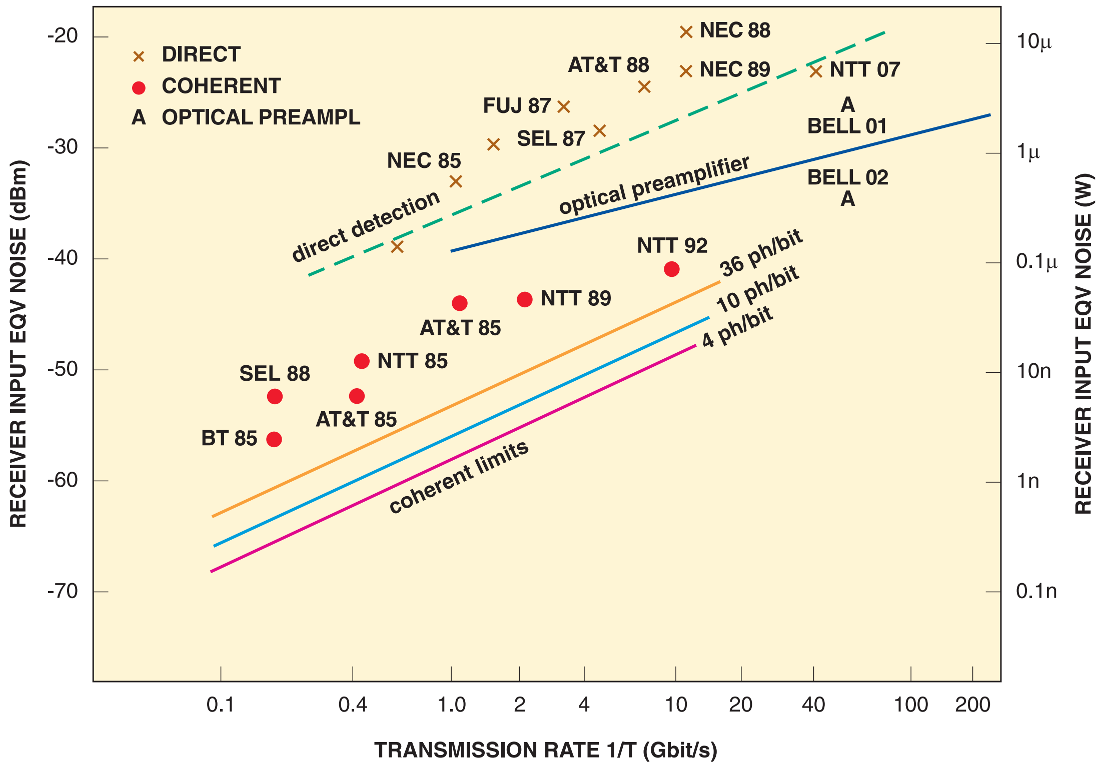
In the chart (figure 1) showing the various receivers' performances, sensitivity data for the optical preamplification photodetector are significantly better than the values of traditional photodetectors with transimpedance amplifiers.

The device's structure (figure 2) is also interesting: the photodiode is in ridge guide like the amplifier section, and made of the same material (MQW) in InGaAs on a substrate and with an InP overcap. As the optical amplifier section operates in direct polarization and the photodiode section is reverse polarized, an isolation area must be interposed (obtained with different techniques, generally by intermixing (5)). The photodiode is long enough to absorb all the radiation, thus preventing back reflection by the chip edge. A taper area helps reduce the mode's elliptic shape, facilitating the coupling with input fiber.

It is interesting to note, in the structure shown in figure 2, that from being planar with vertical input the photodiode has become of the side input type. This structure, well known since the early days of photodetection (3) and used to provide high absorption length, becomes essential at hyperfrequencies, as it allows the separation of the photon absorption function from that of drift of photogenerated carriers: this way, we no longer have to accept the compromise between detection efficiency and bandwidth. In fact, the absorption length (or parameter $1/\alpha$) sets one of the two geometric sizes of the sensitive area, the other one being the mode's width which propagates, fortunately not much bigger than λ, when a single-mode fiber is used at the output. Photogenerated charges are collected transversally to the optical guide, so that the length they have to cover (intrinsic cutoff) can be shortened, and the junction capacitance effect can even be eliminated (extrinsic cutoff) by incorporating it in a coplanar output transmission line for electric signals (figure 2).

MQW:
Multi Quantum Well

Figure 1
Receivers' performances (input equivalent noise according to transmission rate). Receivers with 40Gb/s optical pre-amplifiers are better than direct detection receivers with transimpedance front end (adapted from [3] with data from [1,2]).



The semiconductor amplifier is usually penalized by high insertion loss (e.g. compared to EDFA) in optical fiber coupling, as the spatial mode of semiconductors, all with a high refraction index (typically n=3.5), is much smaller than the fiber's mode. In the integrated receiver, however, the photodiode follows the amplifier directly, which eliminates one of the two coupling losses.

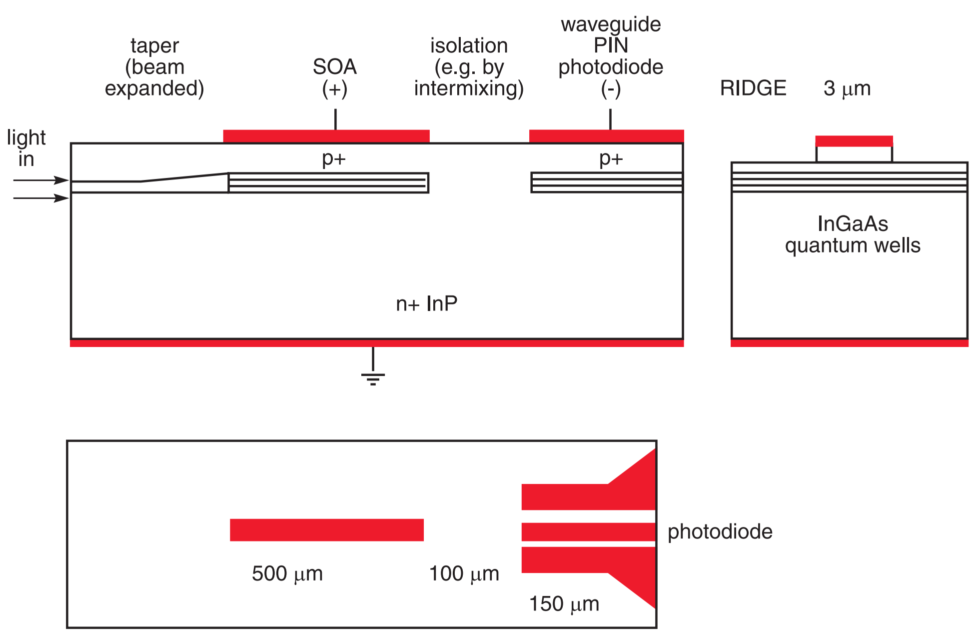
The other significant example of photonic technique proposed as an alternative to traditional electronic approaches is photomixing.

Photomixing is simply the well-known coherent detection (3) which, when performed with an ultrafast photodiode on the two (or more) modes emitted by a laser source, generates a beat signal which may have particularly beneficial properties. A simple configuration for photomixing, also with two Fabry-Perot cavity lasers, is described in another paper presented at this conference (6). In this case, as generally happens, the beat signal at the frequency corresponding to the difference between the two modes (or the associated electric fields) transmitted on the photodiode fluctuates considerably in frequency, and all efforts are directed at circumventing such fluctuation in order to take advantage of the beat.

Conversely, when we initially have a pair of modes very well-defined in frequency, the initial line width is the one which is found in the beat (at most, worsened by √2), i.e. in the electric frequency signal emitted by the photodiode. Therefore, using two narrow-line (≈MHz) or frequency stabilized DFB or DBR lasers (7,8) (it can be as low as Δf≈10 kHz), extremely high frequency signals can be obtained, up to the maximum frequency response of the available photodiode, and with the same Δf as the laser used. Or, frequency stability is transferred from optical frequency to electric frequency.

This is well known in the radioastronomy sector, where the ALMA international cooperation has

Figure 2
Cross section and plan view of the chip of an integrated receiver incorporating the optical amplifier, with QW in InGaAs (λ=1550 nm) and the photodiode with output in coplanar guide. Both components use the same optical guide structure. An isolation layer has been interposed for electric and optical separation. The input guide is tapered for higher fiber coupling efficiency (-3dB).
The 500μm long amplifier's gain is 10-14 dB at a 40-60 mA current.



been active for some time; this initiative's activities include, among others, local oscillators obtained by photomixing (see www.mma.nrao.edu/memos/html-memos, with approximately 350 articles).
Conceptually, we might wonder why the frequency stability of optical sources (laser oscillators) should be markedly superior to the frequency stability of electric sources (electronic oscillators). The reason exists, and is found in the higher $\Delta f/f=1/Q$ selectivity of the optical frequency oscillator, very simply because Q is proportional to the number of wavelengths contained in the size of the laser (resonator) compared to that of millimeter or centimeter waves.
In particular, as demonstrated in another work presented at this conference (9), a semiconductor laser in passive mode-locking, oscillating with numerous longitudinal modes spaced c/2nL (L = cavity length, c = light speed, n = refraction index), may exhibit a particularly good (≈100 kHz) frequency stability. Thus, fabricating a laser with length L = 2400...1200...800μm, the resulting spacing will be c/2nL = 20...40...60 GHz, i.e. the photodiode output is in the range of mm-waves.

It should be noted that a stability of e.g. 100kHz at 60 GHz is not easy to obtain with transistor oscillators (of the appropriate f_T), unless we resort to complicated and expensive frequency stabilization techniques (10).
This is what makes photomixing a promising photonic technique for the generation of microwave signals and carriers.
The condition for the new technique to be successful is to create reasonably high power P_{opt} laser sources, and to make photodiodes able to convert the optical signal into electric signal with high quantum efficiency η.
By way of example, supposing that the mixer photodiode is connected to load R, the electric power obtained $P_{el}=R\ I^2= R((\eta e/h\nu)\ P_{opt})^2$. When $R(\eta e/h\nu)^2\ P_{opt}=1$ the optical power equals the electric power. This condition can also be expressed as: $P_{opt}=1/\ R(\eta e/h\nu)^2$ and for reasonable values (e.g. R = 50Ω, ηe/hν = 1 A/W) we obtain P_0 = 1/50 = 20mW. With $P_{opt}>P_0$ the electric power is greater than the optical power by a factor P_{opt}/P_0, and vice versa with $P_{opt}<P_0$.

Regarding photodiodes, advanced structures with guide or single-carrier traveling wave (uni-traveling carrier) outputs, or MSM (with metal-semiconductor junction) outputs, have been demonstrated to reach 150 GHz easily (11, 12), with record peaks of 500-600 GHz. Even higher frequencies have been reached by fast photoconductors, such as LT-GaAs (low-temperature grown GaAs) and non-linear crystals (GaSe, $ZnGeP_2$, etc.), able to emit Watts at THz frequencies (13, 14).

A currently ongoing research effort in the area of photodiodes aims to obtain high saturation currents at the highest response bands (15), for use in the 60-90 GHz frequency range.

APPLICATIONS IN THE COMMUNICATIONS FIELD

The availability, by mode-locking laser photomixing, of several mW electric power at frequencies ranging from a few GHz to 100 GHz and more, opens the way to several applications in the communications field.

The band around 60 GHz is becoming established as the most adequate for Mobile Broadband Systems (MBS) and WLAN (Wireless LAN) for several reasons: the broad band (≈5 GHz) provided, without license requirements, by the main international standardization bodies (FCC-Federal Communications Commission in the US, ETSI-European Telecommunications Standards Institute in Europe, TTC-Telecommunication Technology Committee in Japan); the high attenuation of free space (which increases with the square of frequency) and absorption of water molecules (16 dB/km at 60 GHz) limit the application to picocells (typical radius 20-100 m) enabling frequency re-use in adjacent cells and communications difficult to intercept, and therefore more secure.

In wireless local and metropolitan networks, in order to provide multimedia services (high-quality videoconferencing, LAN connections between buildings, high definition TV cameras and TVs, wireless IEEE 1394 connections, wireless connections to printers, etc.) requiring high capacity per user (up to1 Gbps), an IEEE 802.16 and 16a standard has already been created to regulate 2- to 66GHz broad-

Figure 3
Radio over Fiber network diagram, with mm-wave radio connection

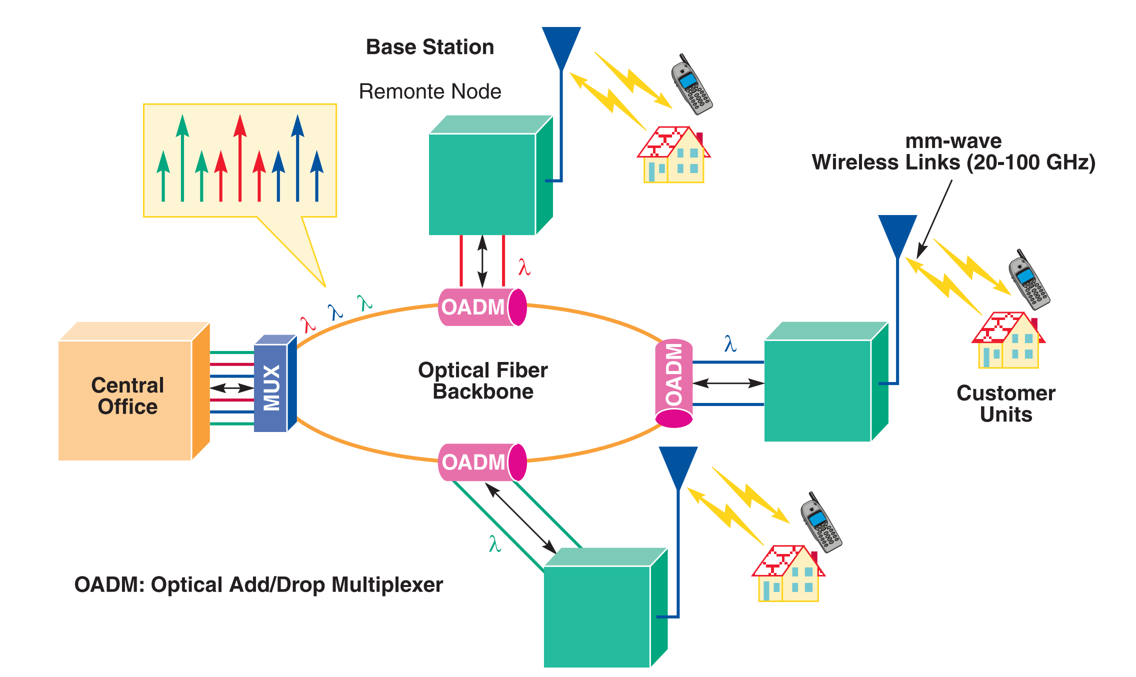
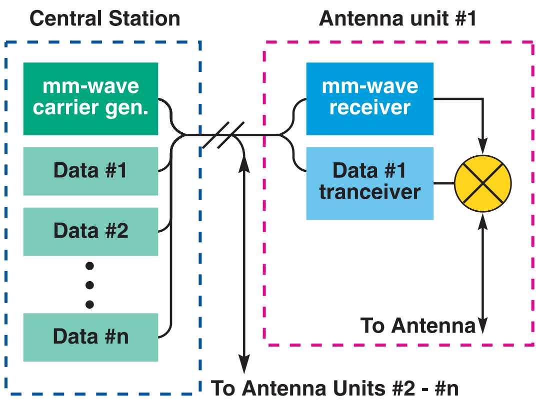


Figure 4
Example of mm-wave carrier generation in the central station [16]



band wireless access. MAN wireless is seen as an economic alternative to optical fiber to solve the problem of cable installation costs in the so-called "last mile".

Another broadband wireless access system is called Hybrid Fiber Radio or Radio over Fiber System. In this case some of base radio stations' most expensive functions are made remote and concentrated in the central station, using optical fiber to connect this station with base radio stations. Using mm-waves for connections between base radio stations and mobile terminals, it is possible to exploit the large bandwidth of these frequencies available to provide high-quality multimedia services, while optical fiber connections enables the transport of high bit rate signals.

Figure 3 illustrates a typical example of Radio over Fiber network. The optical signal's modulation and demodulation takes place in the central station, where the 60GHz carrier can also be generated optically (16) and then, in radio base stations, converted into electric with a photodiode and modulated (see figure 4).

References (17-20) indicate several methods for the optical generation of mm-wave carrier with low phase noise, so that these transmitters can be implemented in applications using high-efficiency modulation techniques like QAM/AM or QAM/FM.

In Japan (20), the same system for the optical generation of mm-wave signal has been proposed as the most promising solution for high-speed home interconnection, to handle satellite TV, PC, CATV services, smart home appliances, etc. (see figure 5).

For all these applications the availability of a low-cost 60GHz transceiver is the key to the widespread use of this technology.

An example of mm-wave integrated transmitter might be a mode-locking laser, whether linear as in (9) or a ring as in (21) (see figure 6). Ring lasers obviously have the advantage of not needing mirrors, but may exhibit bistability and multi-stability problems (22, 23). The mode-locking section can be reverse-biased to increase static absorption. Output power can be raised to 7-15 mW even maintaining the laser output power (≈mW) at moderate levels, with an L=200-500 μm in-line optical amplifier. The coplanar photodetector converts the beat between the laser-generated modes into an electric carrier. Lastly, a patch-type antenna can be installed with the flip chip technique or integrated directly on the same chip. The optical amplifier's current input can be used to modulate the carrier in width and constitute the modulant's input.

For detection, a configuration similar to the one in figure 6 can again be used, which, receiving the optical power and 60GHz signal simultaneously, performs a dual mixing operation: optical mixing to generate the local oscillator, and electric mixing to demodulate the signal received from the antenna (24).

Figure 5
Example of mm-wave video transmission system [20]

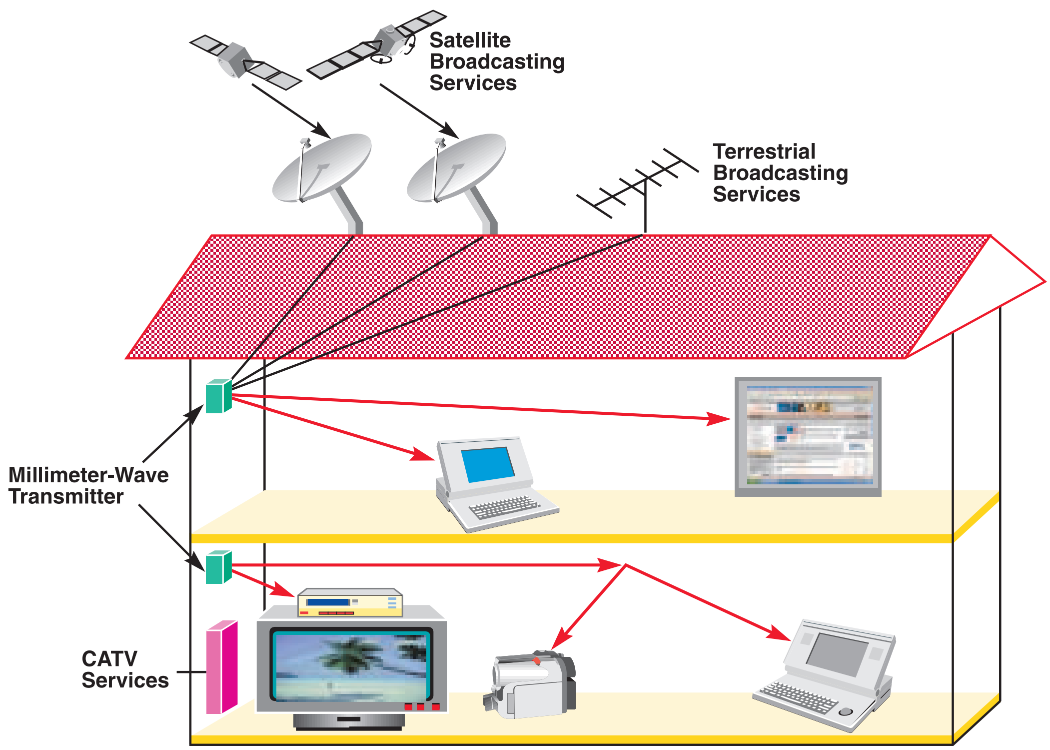
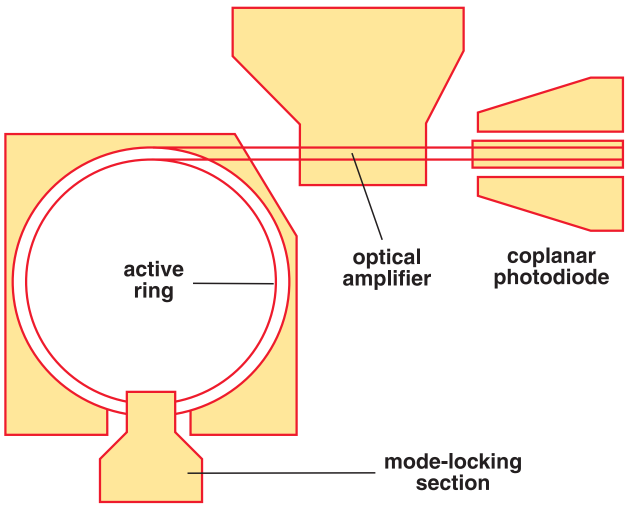
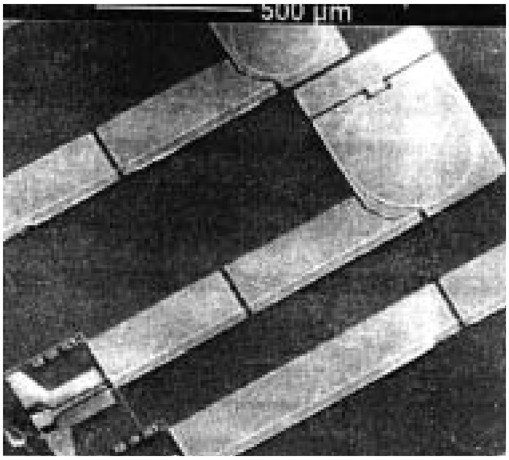


Figure 6
Integrated transceiver for 60GHz carrier generation and photomixing. Left: concept diagram. Right: microphotograph of the chip built by Vawter et al. in [21].





TERAHERTZ IMAGING APPLICATIONS

Several international laboratories have developed equipment for THz frequency imaging (or λ=300 μm, in the EIR or Extreme Infra Red), following the pioneer work of Zhang (Rensselaer Polytechnic Inst., N.Y.) (25).

The interest of this spectral field lies in the partial transparency of fabrics and biological materials (figure 7), which opens the way to new types of diagnostics and provides an immediate alternative to radiographic inspection, without the risk of exposure to ionizing radiation. The system obviously includes optical generator, photodetector, and a point-to-point scanning system (antenna or set of antennas) to synthesize the image.

Figure 7
Examples of THz-Imaging: matches seen inside their box (left), and man with weapon in the belt (right). Frequency: 90 GHz. Power used: 20 mW (left) and 10 W (right). By courtesy of P.Planken TuDelft (left) and QinetiQ (right)

ACKNOWLEDGEMENTS

This work has been carried out within the framework of a cooperation between Telecom Italia Lab and the Optoelectronics Team of the University of Pavia.

REFERENCES

[1] B. Mason, J.M. Geary, J. Freund, A. Ougazzaden, C. Lentz, K. Glogovski, G. Przybylek, L. Peticolas, F. Walters, L. Reynolds, J. Boardman, T. Kercher, M. Rader, D. Monroe, L. Ketelsen, S. Chandrasekhar, L. Buhl: "40Gb/s Photonic Integrated Receiver with -17dBm Sensitivity", Proc. OFC'2002, March 17-22, Anaheim, CA, Post-Deadline paper FB-10.

[2] A.H. Gnauck, S. Chandrasekhar, J. Leuthold, L. Stulz: "Demonstration of 42.7-Gb/s DPSK Receiver with 45 Photons/bit Sensitivity", IEEE Phot. Techn. Lett., Vol. 15 (2003), pp.99-101.

[3] S. Donati: "Photodetectors", Prentice Hall, Upper Saddle River, NJ 1999, Chapter 8.3.

[4] R. Ludwig et al: "Enabling Transmission at 160 Gbit/s", Proc. OFC'2002, Anaheim 17-22 March 2002, paper TuA1, p.1

[5] C.L. Walker, A.C. Bryce, J.H. Marsh: "Improved catastrophic optical damage level from laser with non absorbing mirrors" IEEE Phot. Techn. Lett., Vol.14 (2002), pp.1394 –1396.

[6] M. Norgia, R. Miglierina, G. Giuliani, S. Donati: "Metodo di Caratterizzazione di Fotodiodi a Larga Banda Tramite Photomixing con Laser a Basso Costo", Proc. Fotonica 2003.

[7] D. Wake, C.R. Lima, P.A. Davis: "Optical Generation of Millimeter-Wave Signals for Fiber-Radio Systems using a dual-mode DFB Semiconductor Laser", IEEE Trans. on Microwave Theory and Techniques, Vol.43, No.9, Sept. 1995, pp. 2270-2276.

[8] G. Großkopf, D. Rohde, R. Eggemann, S. Bauer, C. Bornholdt, M.Mohrle, B. Sartorius, "Optical Millimeter-Wave Generation and Wireless Data Transmission Using a Dual-Mode Laser", IEEE Photonics Technology Letters, vol. 12 Dicembre 2000, p.1692-1694

[9] M. Passerini, M. Sorel, P. Laybourn: "Generazione di Segnali RF Mediante Diodi Laser Mode-Locking", Proc. Fotonica 2003.

[10] H. Wang, K.W. Chang, L.T. Tran, J.C. Cowels, T.R. Block, E.W. Lin et al.: "Low phase noise millimeter-wave frequency sources using InP-based HBT MMIC technology", IEEE J. Solid-State Circuits, Vol. 31, Oct. 1996, pp.1419-1425.

[11] N. Shimizu, N. Watanabe, T. Furuta, T. Ishibashi: "InP-InGaAs Uni-Travelling Photodiode with 3dB Bandwidth of over 150 GHz", IEEE Phot. Techn. Lett., vol.10 (1998), pp.412-416.

[12] K. Kato: "Ultrawide-Bandwidth High Frequency Photodetectors", IEEE Trans. Microw. Theory and Techn., vol.47 (1999) pp.1265-1281

[13] Q. Chen, Z. Jiang, G. Xu, X.C. Zhang: "Coherent and Widely Tunable THz Waves based on the Frequency Difference Generation", Opt. Lett., vol.25 (2000), pp.1122-1124.

[14] E. Peyatavit et al., "Terahertz electromagnetic generation via optical frequency difference", IEE Proc.-Optoelectron., Vol.149, No.3, Giugno 2002, pp. 82-87.

[15] K. Williams, R. Esman: "Design Considerations for High-Current Photodetectors" IEEE J. Lightw. Techn., vol.17 (1999), pp.1443-1454.

[16] L.A. Johansson, X. Wang, N.J. Gomes, A.J. Seeds: "Optical Delivery of millimeter-wave carriers using double injection locking", Proc. MTT 2001, Tu-3.4, pp.89-93.

[17] R.P. Braun, G. Grosskopf, et al.: "Optical Microwave Generation and Transmission Experiment in the 12- and 60GHz Region for Wireless Communications", IEEE Trans. on Microwave Theory and Techniques, Vol.46, No.4, April 1998, pp. 320-330.

[18] G., D. Rohde, R. Eggemann, C. Bornholdt, S. Bauer, B. Sartorius, M. Möhrle: "Dual-mode self-pulsating laser for broadband hybrid fiber radio-systems", Proc. ECOC 2000, Mo 1.2.3.

[19] A.J.C. Vieira, P.R. Herczfeld, et al.: "A mode-locked microchip laser optical transmitter for fiber radio", IEEE Trans on Microw. Theory and Techniques, vol.49 (2001), pp.1882-1887.

[20] Y. Shoji, K. Hamaguchi, H. Ogawa: "Millimeter Wave Remote Self-Heterodyne System for Extremely Stable and Low-Cost Broad-Band Signal Transmission", IEEE Trans on Microw. Theory and Techniques, vol.50 (2002), pp.1458-1467.

[21] G.A. Vawter, A. Mar, V. Hietala, J. Zolper, J. Hohimer: "All Optical mm-Wave Generation Using an Integrated Mode-Locked Semiconductor Ring Laser and

Photodiode", IEEE Phot. Techn. Lett. vol.12 (1996), pp.1634-1637.

[22] *M. Sorel, P. Laybourn, G. Giuliani, S. Donati: "Unidirectional Bistability in Semiconductor Waveguide Ring Laser", Appl. Phys. lett., vol.80 (2002), paper 048217.*

[23] *M. Sorel, P. Laybourn, A. Scirè, S. Balle, G. Giuliani, S. Donati: "Alternate Oscillations in Semiconductor Ring Laser", Optics Lett., vol.27 (2002), pp.1992-1994.*

[24] *S. Donati, T. Tambosso: "Device for information transmission and/or reception by means of millimeters wave signals, corresponding module and method" Domanda di Brevetto No.805F/WO/GM (Giugno 2002)*

[25] *O. Graydon: "Terahertz Waves penetrate the World of Imaging", Opt. Laser Europe, Oct.2002, pp.22-24.*

CONTACTS

Silvano Donati
Department of Electronics
University of Pavia
Tel.: +39 0382 505204
donati@ele.unipv.it

Tiziana Tambosso
Telecom Italia Lab
Tel.: +39 011 2285319 - Fax: +39 011 2287140
tiziana.tambosso@telecomitalia.it