Optical sampling using wideband electro-optic modulators

Marc Niklès
Luc Thévenaz
Philippe-Alain Robert, MEMBER SPIE
Jean-Pierre von der Weid*
Swiss Federal Institute of Technology
Metrology Laboratory
CH-1015 Lausanne, Switzerland
E-mail: marc.nikles@de.met.epfl.ch

Abstract. A simple system for optical and microwave signals analysis based on the optical sampling technique is presented. It is novel in requiring only low-frequency detection and electronic components. This is made possible by the use of a commercially available $LiNbO_3$ intensity modulator for processing the light wave. The ultimate performance of the system is discussed, and comparisons with standard detection systems are also made.

Subject terms: optical sampling; electro-optic modulators; optical signal processing; pulsed laser diode.

Optical Engineering 34(7), 2078–2083 (July 1995).

1 Introduction

High-speed optical waveguide switches and modulators are promising components for present and future applications in coherent light-wave communication systems[1,2] and instrumentation.[3,4] Several configurations and materials have been employed in pursuit of larger bandwidths, gallium arsenide and lithium niobate being the most employed electro-optic materials.[5,6] Lithium niobate traveling-wave modulators have been reported[7,8] with modulation bandwidths in excess of 40 GHz. At these frequencies measurements are frequently limited by the finite bandwidth of the photodetector and the electronics, and in addition the signal-to-noise ratio degrades rapidly with increasing electrical bandwidth. Results are usually obtained by deconvolution calculation.

A number of different techniques have been proposed so far to overcome the problem of finite detector rise time in wideband optical waveform analysis. These techniques are usually referred to as optical sampling, since they make use of a short optical pulse as a probe sampler. The first reported optical sampling technique employed a synchronously pumped dye laser producing 5-ps pulses at $\lambda = 600$ nm to analyze the frequency response of a fast Ti-indiffused lithium niobate waveguide switch.[9] Other optical sampling techniques include the use of nonlinear optical mixing by upconversion of the optical waveform with short optical pulses from mode-locked or gain-switched laser diodes,[10,11] or of the Kerr effect induced by short high-power pulses from Nd:YAG lasers.[12] All these techniques involve the use of either high-power lasers or nonlinear optical components and discrete optics, restricting their application to research.

In this paper we report applications of high-speed electro-optic modulators/switches to either optical or microwave signal analysis based on the optical sampling technique used by Alferness et al.[9] We have further developed the method, so that neither bulk optical components nor high-power lasers are involved. The optical pulses are simply produced by a gain-switched semiconductor laser diode, and all the optical components of the system are pigtailed devices. The technique makes use of commercially available devices and is easy to handle. Furthermore the electronic signal analysis requires only low-frequency detectors and amplifiers, allowing a high-gain detection scheme and thus the processing of weak optical signals. In addition, a complete theoretical analysis of the optical sampling in the Fourier domain is presented.

2 Optical Sampling

Let us first consider an optical system consisting of an optical source, an electro-optic intensity modulator, and a photodiode detector as shown in Fig. 1. If the optical source delivers an

* On leave from Pontifica Universidade Catõlica, CETUC, Rio de Janeiro, RJ 22453, Brazil.

Paper SWI-61 received Nov. 15, 1994; revised manuscript received Jan. 27, 1995; accepted for publication Feb. 10, 1995.

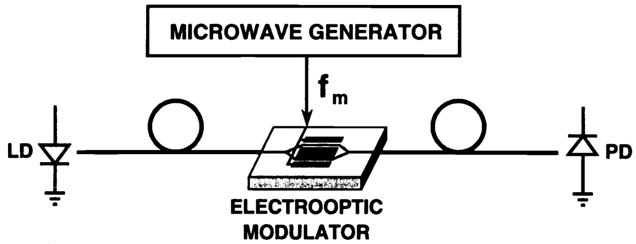


Fig. 1 Schematic representation of an optical system consisting of a semiconductor laser, an external modulator, and a photodetector.

arbitrary, but periodic, waveform with the repetition rate f_0, the time-dependent optical signal launched into the electro-optic modulator can be described by its Fourier series:

$$P_{\text{in}}(t)=\sum_{j=0}^{\infty} a_j \cos(2\pi j f_0 t)+b_j \sin(2\pi j f_0 t)$$

$$=\sum_{j=0}^{\infty} p_j \cos(2\pi j f_0 t+\phi_j) \ , \qquad (1)$$

where p_j is the optical power in the j'th harmonic of the fundamental frequency f_0.

Let us suppose now that the electro-optic modulator is also driven by a periodic electric signal, whose repetition rate is f_m. For any dc bias voltage, the time-dependent power transfer function of the modulator is also described by a Fourier series:

$$H(t)=\sum_{i=0}^{\infty} c_i \cos(2\pi i f_m t)+d_i \sin(2\pi i f_m t)$$

$$=\sum_{i=0}^{\infty} h_i \cos(2\pi i f_m t+\varphi_i) \ . \qquad (2)$$

The output optical signal from the electro-optic modulator is therefore given by the product of the input power and the transfer function. The time origins of the transfer function and the optical signal are chosen to be identical in order to simplify the notation. Different time origins would result in a constant phase shift of the output signal:

$$P_{\text{out}}(t)=\sum_{i,j}^{\infty} h_i p_j \cos(2\pi j f_0 t+\phi_j)\cos(2\pi i f_m t+\varphi_i) \ . \qquad (3)$$

By using elementary trigonometric relations Eq. (3) can be written as

$$P_{\text{out}}(t)=\frac{1}{2}\sum_{i,j}^{\infty} h_i p_j \ \{\cos[2\pi(jf_0+if_m)t+\phi_j+\varphi_i]$$

$$+\cos[2\pi(jf_0-if_m)t+\phi_j-\varphi_i]\} \ . \qquad (4)$$

Let now the two frequencies f_0 and f_m be very close, $f_m=f_0-\Delta f$, so that

$$P_{\text{out}}(t)=\frac{1}{2}\sum_{i,j}^{\infty} h_i p_j (\cos\{2\pi[(j+i)f_0-i\ \Delta f]t+\phi_j+\varphi_i\}$$

$$+\cos\{2\pi[(j-i)f_0+i\ \Delta f]t+\phi_j-\varphi_i\}) \ . \qquad (5)$$

If the bandwidth of the detector is much smaller than the frequencies f_0 and f_m, the high-frequency components of Eq. (5) will be averaged out, and only low-frequency components will remain in the detected optical signal:

$$S(t)=S_0+\frac{1}{2}\sum_{i,j=0}^{\infty} h_i p_j \cos(2\pi i\ \Delta f\ t+\phi_i-\varphi_j) \ . \qquad (6)$$

In the optical sampling technique only the time-dependent part of Eq. (6) is of importance, when either the optical light signal or the modulation function can be approximated by a Dirac impulse function. For instance, when the emitted light signal is an optical pulse whose duration is much smaller than its repetition time $1/f_0$, all coefficients p_j in Eq. (6) are close to unity. Furthermore, if the modulation function $H(t)$ is a very short impulse compared to its repetition time, the coefficients h_i are all close to unity. The simplest case consists of a periodic optical signal being analyzed by a short electro-optic gate. By using a driving frequency f_m close to the optical signal repetition rate f_0, only the terms for $j=i$ will fall within the detector bandwidth, and the ac part of the detected signal will be given by

$$S(t)=g\sum_{i=0}^{\infty} p_i \cos(2\pi i\ \Delta f\ t+\phi_i-\varphi_i) \ , \qquad (7)$$

where g is an arbitrary constant that includes the detector sensitivity, the electro-optic attenuation, etc. Equation (7) means that the detected signal is a replica of the initial optical signal with a frequency shifted from its initial value f_0 down to the beat frequency $\Delta f=f_0-f_m$ and is phase shifted from φ_i to $\phi_i-\varphi_i$. This phase shift can be adjusted by introducing either an electrical or an optical delay line.

Using this principle, the analysis of a periodic optical signal can be easily performed by driving an electro-optic modulator with an impulse train whose repetition rate is close enough to the optical signal repetition rate so that all the relevant harmonics of the fundamental beat frequency are smaller than the detector bandwidth. This avoids distortion of the replicated signal.

Impulse train functions are usually generated by using microwave comb generators whose frequency tunability is somewhat limited, so that the analysis of an optical signal of arbitrary frequency may likewise be limited. However, the optical gate can be driven close to any arbitrary subharmonic frequency f_0/k of the optical signal. In this case, only the terms with $i=kj$ will be detected and the frequency scale will accordingly be downshifted.

This principle is easily understood in the frequency-domain representation shown in Fig. 2. In (a), the two signals have frequencies close to each other and the power spectrum of the optical signal will be reproduced at a downshifted scale. In (b), the optical gate is driven at half the frequency of the optical signal, so that only even harmonics will give rise to a detected beat signal. It is clear that if the optical gate is driven at a faster rate, it is impossible to probe all the harmonics of the optical signal, and the reproduced signal will be correspondingly distorted.

3 Electro-optic Modulator

The electro-optic modulator used in our experiment was a commercial $LiNbO_3$ traveling-wave modulator pigtailed with

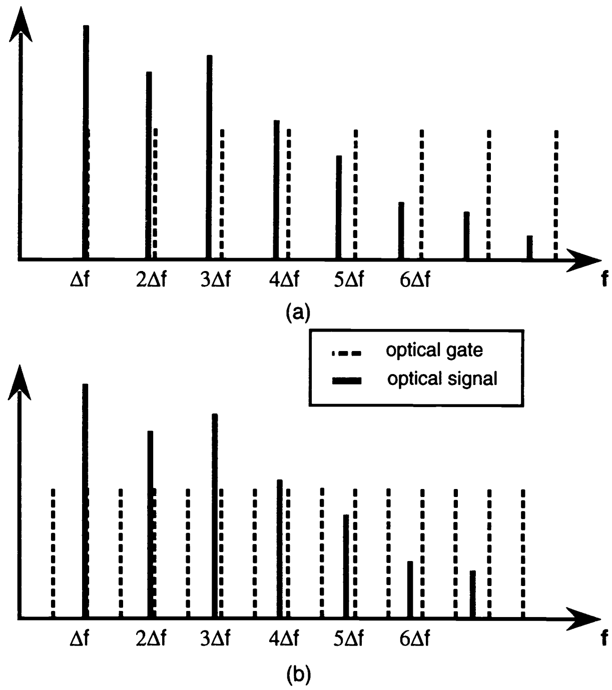


Fig. 2 Frequency representation of electric and optical signals. (a) The two signals have very close frequencies and give rise to a beat signal with base frequency Δ *f*. (b) The optical gate is driven at half the frequency of the optical signal frequency.

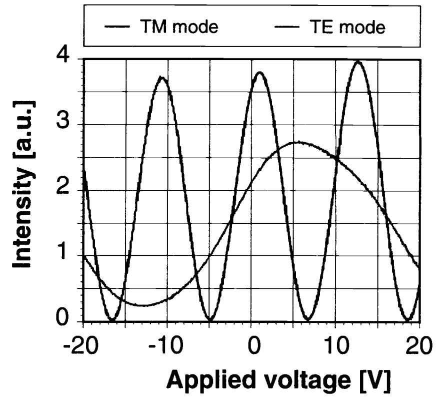


Fig. 3 Electro-optic response of the traveling-wave intensity $LiNbO_3$ modulator for both TM and TE modes.

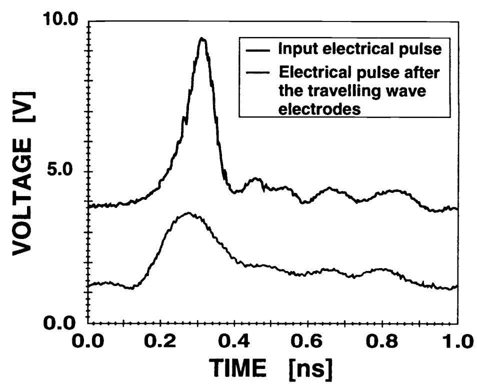


Fig. 4 Electrical modulation pulses before and after propagation through the traveling-wave electrodes.

polarization-maintaining single-mode fibers. The device's attentuation and its characteristic curve of transmission versus applied voltage depend on the input light polarization. The TM mode is observed to be more efficient for light modulation, as can be seen in Fig. 3.

When biased in the linear region (3.5 V for theTM mode), the device acts as a light intensity modulator with a linear response, provided that the amplitude of the modulation signal is small enough. If the device is used as an optical gate with this bias voltage, it must be driven by fast electric pulses of amplitude not greater than 1 V. In this case the bandwidth of the optical gate will be mainly limited by the response time of the electrodes. In our experiment, this response time was measured by comparison of the input and output electric pulses, both measured with a sampling oscilloscope with a 25-ps-rise-time sampling head. Figure 4 shows the input pulse obtained using a comb generator and the corresponding output from the traveling-wave electrodes. As shown, the electrodes system has an 85-ps risetime, limiting the 3-dB modulation bandwidth of the device electrodes to about 3 GHz.

To main problems arise when using the electro-optic device as an optical gate biased in the linear region: the small modulation depth imposed by the linear condition and the inconvenient tail introduced in the pulse response by the device electrodes. These problems may be overcome by using a bias voltage that places the device in a minimum (or maximum) of its electro-optic response. In this case the nonlinear response not only will eliminate the small tail but also will shorten the optical gate with respect to the electrical pulse, giving superior performance. Furthermore the modulation depth can be much larger than in the linear regime, the only restriction being the saturation behavior that arises when the driving electric pulse brings the device beyond the linear region (peak voltage greater than 5 V). The calculated pulse response obtained with an electric pulse similar to that shown in Fig. 3 results in an optical gate width of 100 ps instead of the 165 ps observed in the linear regime. The inconvenient tails and wings are all eliminated, giving rise to a clean bell-shaped optical gate narrower than the driving electric pulse.

4 Characterization of the Electro-optic Gate

The experimental setup used to measure the characteristic response of the electro-optic gate is shown in Fig. 5. A 10-MHz master clock was used to drive two rf generators at frequencies f_0 and $f_0 - \Delta f$. The frequency f_0 was chosen to be either 100, 250, or 500 MHz, depending on the comb generator's characteristics. The beat frequency Δf was chosen to be respectively 100, 250, or 500 Hz, so that the beat frequency was always 10^6 times smaller than the original rf frequency. One of the generators was used to drive ≈ 8-V, 200-ps-rise-time electric pulses on a 1.3-μm semiconductor laser, which operated in gain-switched condition. The 50-ps laser pulses were launched into the electro-optic device after passing through a set of polarization-control fiber loops to match the input polarization with the TM mode of the device.

The second rf generator was used to drive 6-V, 75-ps electric pulses on the electro-optic modulator electrodes. The

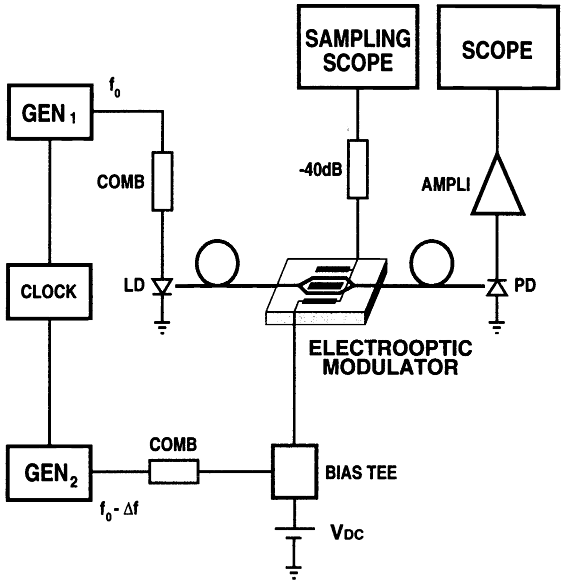


Fig. 5 Experimental setup used in the optical sampling technique.

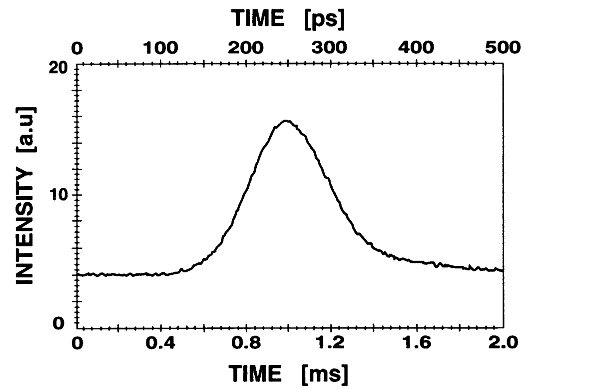


Fig. 6 Measurement of the optical gate generated by the intensity modulator, using the optical sampling technique (the upper scale represents the actual time scale, whereas the lower shows the time scale on which the measurement was performed).

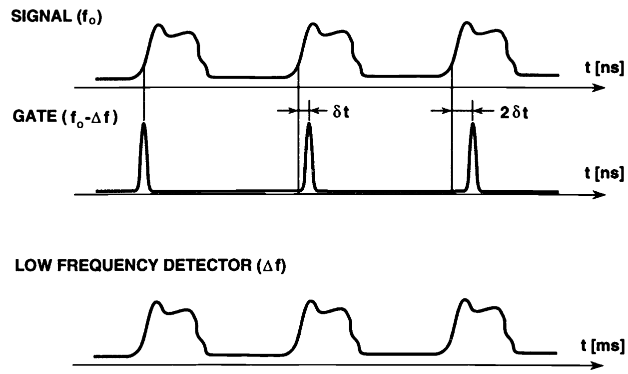


Fig. 7 A short optical gate is used to sample an arbitrary periodic optical waveform, which is replicated in the low-frequency domain.

pulses were then attenuated and measured with the sampling oscilloscope. A bias tee was used to adjust the operating conditions of the modulator. The output signal was connected to an InGaAs pin photodiode followed by a high-gain operational amplifier. By changing the feedback resistance, the gain and bandwidth of the detecting system were controlled, so that the low-frequency electronics never introduced signal distortion.

In this configuration, the short optical pulses were used to probe the transfer function of the electro-optic modulator, so that it could be completely characterized in the time domain. Figure 6 shows the measured pulse response of the electro-optic modulator. The calculated gate width, as discussed above, should be 100 ps, to be compared with a measured width of 112 ps. This difference arises from the finite width of the optical pulse used to probe the electro-optic device. Comparison of the measured and calculated gate widths allows an estimation of the optical pulse width, which turns out to be close to 50 ps, as previously mentioned.

5 Optical Signal Analysis

An arbitrary periodic optical signal waveform can be analyzed by the electro-optic sampler by adjusting the sampling frequency close to the unknown frequency and looking at the detected signal on a low-frequency oscilloscope, as shown in Fig. 7. Knowledge of the beat frequency as well as the optical-gate repetition rate allows calibration of the unknown signal frequency and also the frequency-shift factor.

The ultimate limits of the optical sampler are shown in Fig. 8. Here the 1.3-μm-laser double pulse is generated by a 200-ps-rise-time, 10-V electric pulse directly coupled to the laser anode. The double structure is clearly recognized, but the system is limited by the resolution of the optical sampling gate to 100-ps rise time.

6 Microwave Signal Analysis

The optical sampling technique can also be used to analyze fast periodic electric signals, provided that their amplitude is small enough to operate the electro-optic modulator in the linear regime. Figure 9 shows a comparison of the optically sampled signal with the electrically sampled detection. It also gives a representation of the distortion of an arbitrary signal as it propagates through the traveling-wave electrodes. The electric detection used a sampling oscilloscope with a 25-ps-rise-time sampling head, whereas the optical pulse used as gate sampler had ≈50-ps rise time. Figure 9(a) shows the input waveform, containing a sharp pulse plus a lower-frequency component. After passing through the electrodes in Fig. 9(b), the sharp peak is reduced and its width increased due to the limited bandwidth of the waveguide electrodes. Figure 9(c) shows the optically sampled signal; the waveform is nice and clean compared to the electrically sampled waveform. Because the distortion of the electrical signal on the electrodes is progressive, the optical signal shows a slightly sharper peak than Fig. 9(b).

7 Conclusions

The direct detection and signal processing of high-frequency optical signals is made difficult by the lack of broadband amplifiers and by the excess noise in microwave electronics, dramatically decreasing the signal-to-noise ratio. The use of the optical sampling technique translates the relevant information to the low-frequency range, so that a noiseless and low-cost detection scheme and accurate measuring instru-

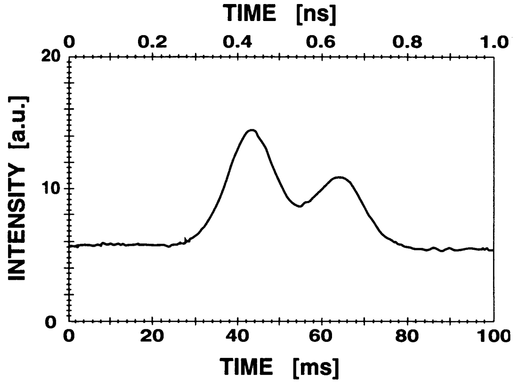


Fig. 8 Measurement of an optical double pulse generated by a 1.3-μm semiconductor laser using the optical sampling technique.

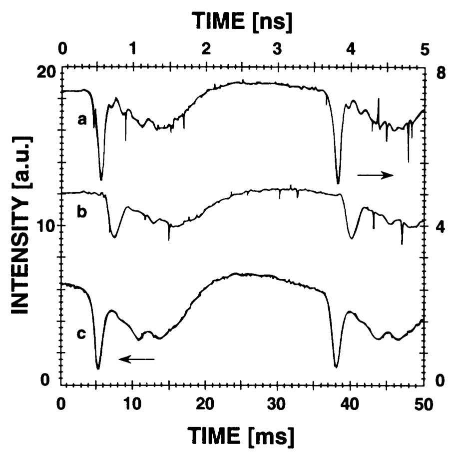
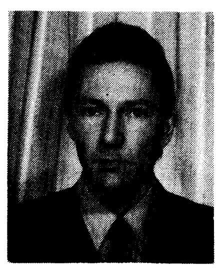


Fig. 9 (a) Representation of an arbitrary periodic electrical signal measured with a standard electrical sampling unit, (b) the same waveform measured after the traveling-wave electrodes, and (c) the corresponding optical signal measured using the optical sampling technique.

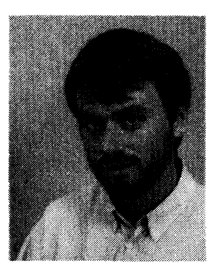
mentation are all that is required. Thus the processing of a weak optical signal of a few nanowatts is still possible with high accuracy, which is not achievable using a standard detection scheme. In these conditions, optical sampling with electro-optic modulators is a very convenient technique for optical signal analysis and even for microwave analysis. Furthermore, this technique can also be very powerful for bandwidth characterization of optical guided-wave modulators over a range of several gigahertz.[7,13] In the case of optical signal analysis the limitations of the optical sampling techniques are mainly imposed by the bandwidth of the electro-optic modulators. However, faster electro-optic devices are being developed, so that limiting bandwidths as high as 40 GHz can be expected in the near future, whereas 20-GHz modulators are now commercially available. On the other hand, in the case of microwave signal analysis, the limiting factor appears to be the short optical pulses. The recent advances in the field of fiber laser sources show that generating subpicosecond optical pulses is getting easy, using mode-locked fiber laser or figure-8 laser sources. These developments open new perspectives for optical sampling techniques.

References

1. T. Mizuochi, T. Kitayama, S. Kawanaka, M. Izutsu, and T. Sueta, "17-GHz band fiber optic transmission experiment using a $LiNbO_3$ resonant type modulator," Paper WM25, in *OFC'90, Technical Digest,* Optical Society of America, Washington, D.C., p. 124 (1990).
2. S. H. Korotky and R. C. Alferness, "Waveguide electrooptic devices for optical fiber communication," in *Optical Fiber Telecommunication II,* Academic Press, New York (1988).
3. L. Thévenaz and J.-P. Pellaux, "Group delay measurement in single mode fibers with true picosecond resolution using double optical modulation," *J. Lightwave Technol.* **LT6**(10), 1470–1475 (1988).
4. P. Heinday, R. Wong, and R. L. Jungerman, "20-GHz lightwave component analysis instrumentation using an integrated optical modulator," Paper WM26, in *OFC'90 Technical Digest,* Optical Society of America, Washington, D.C., p. 125 (1990).
5. R. C. Alferness, in *Guided-Wave Optoelectronics,* T. Tamir, Ed., Springer-Verlag, Berlin (1988).
6. S. Y. Wang and S. H. Lin, "High speed III-V electrooptic waveguide modulators at $\lambda = 1,3$ μm," *J. Lightwave Technol.* **6**(6), 758–771 (1988).
7. S. K. Korotky, G. Eisenstein, R. S. Tucker, and G. Raybon, "Optical intensity modulatin to 40-GHz suing a waveguide electrooptic switch," *Appl. Phys. Lett.* **50,** 1631–1633 (1987).
8. S. K. Korotky and J. J. Veselka, "Efficient switching in a 72-Gbit/s Ti:$LiNbO_3$ binary multiplexer/demultiplexer," Paper TUH2, in *OFC'90 Technical Digest,* Optical Society of America, Washington, D.C., p. 32 (1990).
9. R. C. Alferness, N. P. Economon, and L. L. Buhl, "Picosecond optical sampling technique for measuring the speed of fast electro-optic switch/modulators," *Appl. Phys. Lett.* **37**(7), 597–599 (1980).
10. T. Kanada and D. L. Franzen, "Optical waveform measurement by optical sampling with a mode-locked laser diode," *Opt. Lett.* **11**(1), 4–6 (1986).
11. D. L. Franzen, Y. Yamabayashi, and T. Kanada, "Optical sampling with gain switched, pulse compressed distributed feedback laser diodes," *Electron. Lett.* **23**(6), 290–291 (1987).
12. K. Kitayama, Y. Kimura, K. Okamoto, and S. Seikai, "Optical sampling using an all-fiber optical Kerr shutter," *Appl. Phys. Lett.* **46**(7), 623–625 (1985).
13. J.-P. von der Weid, M. Niklès, L. Thévenaz, J.-P. Pellaux, and P. Robert. "Simple techniques for bandwidth measurements of optical guided-wave modulators, Paper WeB. 8. 5, in *Proc. ECOC'91, SEE, Paris (France),* p. 533 (1991).



Marc Niklès graduated from the Swiss Federal Institute of Technology of Lausanne (EPFL), Department of Microtechnology, in 1989. In 1990 he joined the Metrology Laboratory of the Swiss Federal Institute of Technology of Lausanne Switzerland, where he developed metrological facilities for characterizing integrated optical devices and applications using optical signal processing. He is now currently working towards his PhD on stimulated Brillouin scattering in optical fibers, for which he has performed reference measurements of Brillouin scattering parameters using a novel method and developed a new fiber optic distributed temperature sensor.



Luc Thévenaz received the BSc degree in astrophysics from the Observatory of Geneva, Switzerland, in 1982, and the PhD degree in physics from the University of Geneva, Switzerland, in 1988. In 1983 he joined the Group of Applied Physics at the University of Geneva, where he was engaged in research work on single-mode fibers measurement techniques. In 1988, he joined the Laboratory of Metrology of the Swiss Federal Institute of Technology in Lausanne, Switzerland, where he presently occupies a senior research position and gives three courses. He manages many research projects dealing with guided-wave measurement techniques, Brillouin-scattering optical fiber sensors, nonlinearities in fibers, and spectroscopic techniques. In 1991, he visited the University of Rio de Janeiro and Stanford University, where he participated in the development of a Brillouin laser fiber gyroscope.

Philippe-Alain Robert: Biography and photograph appear with the paper "Measuring integrated optical circuits using a low-coherence light source" in this issue.

Jean-Pierre von der Weid received the PhD degree in physics from Pontificia Universidade Catholica (PUC), Rio De Janeiro, Brazil, in 1975. He joined the Physics Institute, University of Neuchâtel, Switzerland, working on solid-state physics. He then returned as professor to the Physics Department of PUC University, Rio De Janeiro, Brazil. He spent one year in 1986 in the Applied Physics Group, University of Geneva, Switzerland, where he investigated chromatic dispersion and birefringence in optical fiber measurement techniques. In 1990 he visited the Metrology Laboratory of the Swiss Federal Institute of Technology of Lausanne, Switzerland, where he investigated the applications of integrated optical devices for signal processing. He is presently the head of the Center of Study in Communication (CETUC) of PUC University, Rio De Janeiro, Brazil.