Techniques for bandwidth measurements of optical guided-wave modulators

Marc Niklès, Luc Thévenaz and Philippe Robert

High-speed optical guided-wave switches and modulators are promising components for present and future applications in lightwave communication and measurement systems, or more generally for optical signal processing purposes. Integrated electro-optic modulators with bandwidth extending over a few gigahertz and low drive voltages are now commercially available. Due to their potential applications, bandwidth characterization is an important feature of the metrology of these devices and is often limited by the finite response time of the detection system. In this paper, the bandwidth limitations of the electro-optic modulators are discussed and we report two techniques for bandwidth measurements, which present the great advantage to use only low-frequency detection. This was made possible by processing the lightwave directly, using either a sampling technique with a narrow optical pulse as a probe signal or a direct optical spectrum analysis of the modulated signal.

Méthodes de mesure de la bande passante des modulateurs optiques intégrés

Les modulateurs et commutateurs optiques intégrés sont des composants très prometteurs pour les futures communications optiques à grande échelle, de même que dans le domaine des capteurs, ou plus généralement chaque fois qu'un traitement du signal optique est nécessaire. Plusieurs types de modulateurs électro-optiques possédant une bande passante de plusieurs gigahertz et de faibles tensions de commande sont maintenant disponibles sur le marché. De par leurs applications potentielles, la bande passante est une grandeur importante de la métrologie de ces modulateurs. Les mesures sont souvent limitées par le temps de réponse du système de détection. Dans cette communication, les problèmes de la bande passante des modulateurs, liés à leur structure, sont abordés et deux méthodes de caractérisation sont présentées. Ces dernières présentent l'originalité de ne faire appel qu'à un système de détection à basse fréquence, grâce à un échantillonnage du signal de modulation par l'intermédiaire d'impulsions optiques très courtes d'une part, ou d'autre part, grâce à une analyse directe du spectre optique du signal modulé.

Messmethoden für die Bandbreite von integriert-optischen Modulatoren

Lichtwellenschalter und -modulatoren sind unentbehrliche Komponenten für gegenwärtige und zukünftige Anwendungen in der optischen Nachrichtentechnik und Sensorik. Inzwischen sind einige integriert-optische Modulatoren auf elektrooptischen Materialien mit einer Bandweite von mehreren Gigahertz und niedrigen Betriebsspannungen bereits auf dem Markt erhältlich. Hinsichtlich möglicher Anwendungsbereiche ist die Messung der Bandbreite dieser Komponenten von grosser Bedeutung und wird oft von der Bandbreite des Detektors begrenzt. In diesem Artikel werden die Bandbreitebegrenzungen dieser elektrooptischen Modulatoren beschrieben. Dabei werden zwei neue niederfrequente Messverfahren vorgestellt, in denen das modulierte Signal entweder durch sehr kurze Impulse abgetastet oder dessen optisches Spektrum direkt analysiert wird.

1. Introduction

The increasing data rate capabilities of optical links require modulation devices with ultra-broad bandwidth. For this purpose, integrated electro-optic modulators are todate the most suitable devices, due to their flat frequency response extending over several gigahertz and their low drive voltage requirement. Several configurations and materials have been proposed seeking for larger bandwidth, gallium arsenide and lithium niobate being the most employed.

Bandwidth characterization of these devices is therefore of prime importance considering their key-function in the transmission link. In most available measuring systems the frequency response of the optical devices is directly electrically measured, using a microwave measurement apparatus after detection of the light signal using an ultrabroad band detector [1] [2]. For accuracy purposes and full frequency coverage, high standard instrumentation has to be used and requires the according investments. Besides, the advanced technology of integrated optics evolves fast; high speed switches and modulators have been reported with modulation bandwidth extending up to 40 GHz [3]. Dealing with such high frequencies causes increasing problems and bandwidth measurements are frequently limited by the finite response time of the detector and the amplification circuit. Results are usually obtained by de convolution calculus.

In this paper we report two techniques, developed for bandwidth measurements which involve instrumentation and devices that most laboratories can afford [4]. With these methods, we basically have aimed at solving the problem of the finite bandwidth of the detection system. The electrical part of the measuring system is greatly simplified and has the further advantage to use only *low-frequency* detection and measurement apparatus, resulting in a drastic cost reduction, a very uniform response and an improved dynamic range. This was achieved by taking as much as possible advantage of the optical nature of the signal by directly processing the lightwave, using either a sampling technique with a narrow optical pulse as a probe signal or direct optical spectrum analysis.

2. Electro-optic modulators

The field of integrated optics is now pursued along three primary technology fronts: semiconductor, lithium niobate and glass [5]. While the fabrication, material and sometimes the terminology is technology dependent, the underlying principles and structures are the same. However, only lithium niobate waveguide devices are currently commercially available, and high-speed modulators continue to be the primary candidate for large scale applications. For this reason, we will focus in this paper on lithium niobate devices although the measurement methods described here are perfectly relevant for any types of modulators.

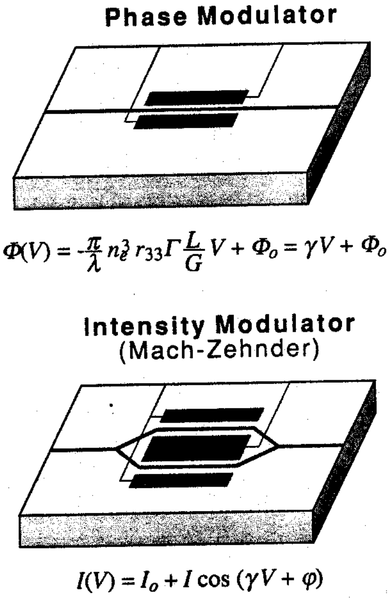
2.1. Electro-optic effect

In certain types of crystals, an intense electric field introduces a change in the refractive index. This is the so-called linear electro-optic effect (Pockels effect), since the change in the refractive index is proportional to the applied electric field, and it provides a convenient way to control intensity, phase or polarization of a propagating beam. It is important to note that even tough the electrooptic effect is very small, low drive voltage can be used. As a matter of fact, in integrated optics the guided nature of the light can here be fully exploited and the design of relatively long electrodes alongside of the wave guide makes the total effect to be increased.

In the lithium niobate based technology, the elevation of the refractive index necessary to the fabrication of a wave guide usually results from titanium diffusion in the substrate. The wave guide configuration is photolithographically impressed on the crystal surface. A voltage applied to the different electrodes placed over or along the wave guide creates the internal electric field necessary to introduce a change in the refractive index and thus to enable the electro-optic modulation of the guided wave. The way in which the index changes gives rise to intensity or phase modulation, polarization control, filter turning optical switching, etc. depending only upon the device configuration [6].

The simplest wave guide electro-optic device is surely the phase modulator, in which the linear electro-optic induced change causes a phase shift of the guided light. It is also the basic element of most of the more complex structures. The total phase shift is proportional to the applied voltage V and depends on several parameters, but mainly on the ratio between the interaction length L and the electrodes gap G. The absence of diffraction of a guided beam allows to greatly increase this ratio in comparison with the usual bulk optic Pockels cell. The location and the design of the electrodes intend to maximize the electrical field/optical mode overlap parameter Γ. Finally, the crystal orientation should be chosen to use the largest electro-optic coefficient, r_{33} (=30.9 x 10^{-10} cm/V).

The intensity modulator consists of a phase modulator inserted in one arm of a Mach-Zehnder interferometer. The phase modulator here enables control of the phase difference between the two interferometer arms. Intensity modulation arises from constructive and destructive interferences created after recombination of the two interfering beams. A phase and an intensity modulator are schematically shown in Fig. 1, with their corresponding transfer function.



$$\Phi(V) = -\frac{\pi}{\lambda} n_e^3 r_{33} \Gamma \frac{L}{G} V + \Phi_o = \gamma V + \Phi_o$$

$$I(V) = I_o + I \cos(\gamma V + \varphi)$$

Fig. 1: Electro-optic phase and Intensity modulators with their respective transfer function.

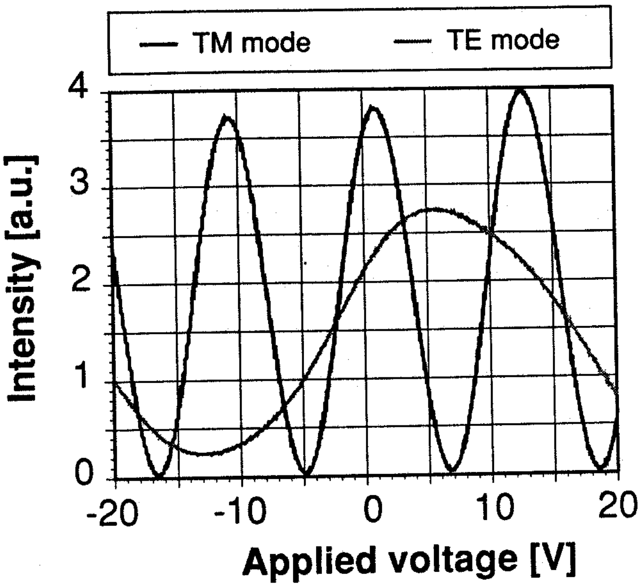


Fig. 2: Electro-optic response of an intensity modulator for both TE and TM modes.

The typical electro-optic response of an intensity modulator is shown in Fig. 2 for both TE and TM modes, TM being three times more efficient for light modulation. When biased in the linear region (around 3 volts), modulation voltages of a few volts are sufficient to operate the electro-optic modulation. The modulator design aims at a low drive voltage and a large modulation bandwidth. As the drive voltage decreases for the increasing interaction length *L* the achievable bandwidth also scales as *1/L* as explained below. Therefore for a given wavelength the geometric parameters Γ/G are optimized in order to minimize the product *VL*.

2.2 Modulation bandwidth

The potential bandwidth of electro-optic modulator is in practice always limited by distributed circuit effects. The electro-optic effect is an electronic phenomenon that has a subpicosecond response time. The achievable modulation bandwidth depends upon several factors. Most important is the electrode type, lumped or traveling wave, schematically shown in Fig. 3. The difference between these two electrode types is the electrical lines and termination. In the case of lumped electrodes, the modulation bandwidth is only restricted by the time constant of the lumped-circuit. The parallel resistor is used to allow broad-band matching to the impedance of the driving source, typically 50Ω. Therefore the modulation bandwidth is then determined by the RC time constant, while the capacitance C of the electrodes is linearly proportional to their length, approximately 2 pF/cm. This leads to a commonly encountered 3 dB modulation bandwidth of about 2.5 GHz. In the traveling wave design, the set of electrodes is by itself a part of the driving transmission line. In this case the bandwidth is not limited by the electrode charging time but rather by the mismatch between the optical and microwave signal velocities. In LiNb0$_3$, the optical wave travels actually almost twice as fast as the RF driving signal. Therefore the optical signal doesn't experience the same electrical field effect over the entire electrode length. It can be shown that the bandwidth is consequently limited to 9.6 GHz cm [6].

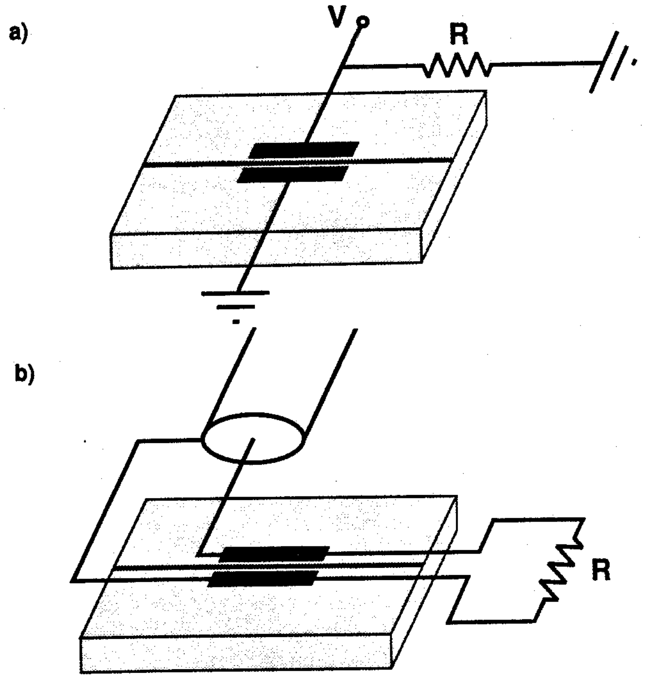


Fig. 3: a) Lumped electrodes b) Traveling wave electrodes.

Several methods have been developed to overcome the ultimate limit of velocity mismatch of the optical and electrical signals. They generally fall into two different categories: real-velocity-matching or artificial-velocity-matching. In the former case the two effective indexes of refraction are equalized by properly designing the electrodes, whereas in the second case, the frequency response is shifted to some arbitrarily high frequency [7].

3. Electrical response of the electrodes

As discussed previously, the electrode type plays an important role in the modulation bandwidth of an electro-optic modulator. However, the measurement of the frequency response of the electrodes doesn't always yield the actual bandwidth of the modulator. Especially in the case of traveling-wave modulator, such a measurement should

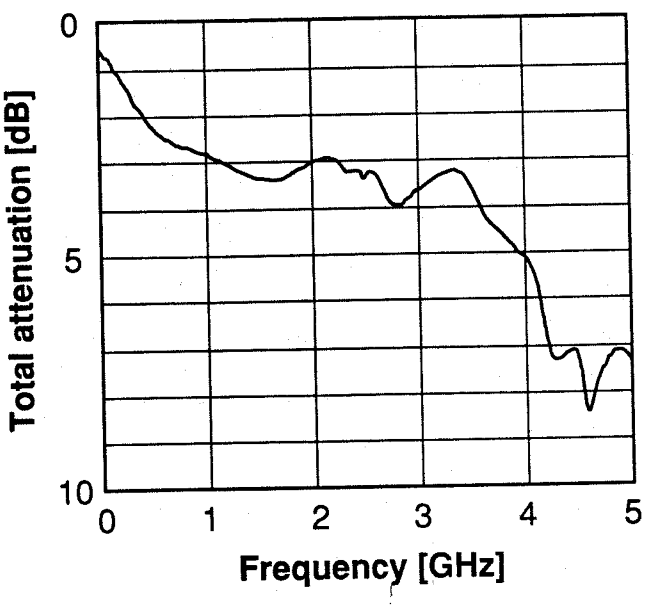


Fig. 4: Frequency response of the traveling wave electrodes.

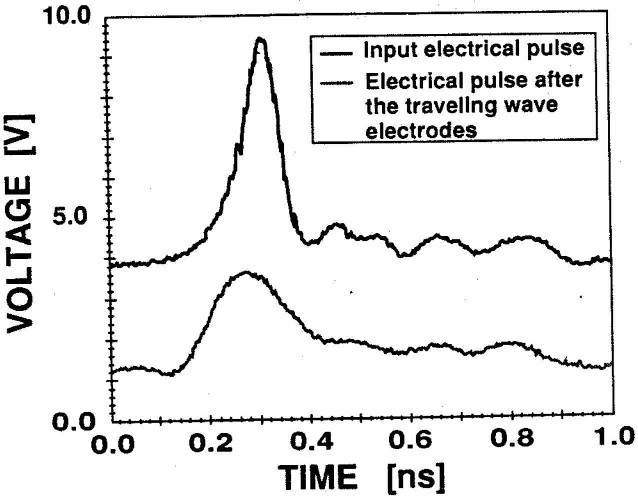


Fig. 5: Electrical modulation pulses before and after propagation through the traveling wave electrodes.

lead to an over valuation of the bandwidth, and only the analysis of the optical modulated signal can give the actual bandwidth. Figure 4 represents the electrodes frequency response of a traveling wave modulator. Besides, an arbitrary electrical signal will be distorted as it propagates through the traveling wave electrodes. Fig. 5 shows a comparison between the input and output modulation signal. The input wave form is made of a sharp pulse and lower frequencies components. After passing through the electrodes, the sharp peak is reduced and its width increased due to the limited bandwidth of the traveling wave electrodes. Because this degradation is progressive, the electro-optic modulation is not uniform over the entire length of the electrodes, resulting in a distortion of the modulated optical signal.

4. Bandwidth measurement by analysis of the optical spectrum of the modulated signal

A Fabry-Perot interferometer or etalon is the simplest optical resonator. Two parallel mirrors constitute a cavity in which an infinite number of partial waves produced by reflections can interfere [8]. The maximum transmission occurs for a given wavelength when the mirrors gap is equal to an integer multiple of the wavelength. The peak transmission can be tuned by changing the cavity length. This property is utilized to operate the etalon as a scanning interferometer. The optical signal to be analyzed is launched into the etalon while its length is being swept. If the width of the transmission peaks is small compared to the spectral components of the optical beam, the output of the Fabry-Perot interferometer is a replica of the spectrum of the incident optical signal. The width of the transmission peak depends on the reflectivity of the surfaces constituting the cavity, the higher the reflectivity, the sharper the transmission peaks and consequently the better the resolution.

When a continuous-wave optical signal is modulated by an external modulator, discrete sidebands are created in the optical spectrum (provided that the source is coherent and single-frequency). Therefore the effect of modulation can be directly observed in the spectral domain by using a Fabry-Perot etalon. This kind of investigation is particularly relevant for phase modulators, since the phase modulation of an optical beam is not directly detectable. Let's consider that latter case. A phase modulated optical wave can be expressed as:

$$E(t) = Re\left\{E_o e^{j\left(\omega_o t + \Delta\phi \cos \omega_s t\right)}\right\} = E_o \cos\left(\omega_o t + \Delta\phi \cos \omega_s t\right)$$

where $\Delta\phi$ and ω_s are the amplitude and frequency of the phase modulation. Using the trigonometric formula and Bessel's series expansion, we can write :

$$E(t) = E_o\left[C_o + \sum_{i=-\infty}^{+\infty} C_i \cos\left((\omega_o + i\omega_s)t + \varphi\right)\right]$$

where the C_i coefficients are the amplitudes of the created sidebands. The sidebands spacing is equal to the modulation frequency, that is in the gigahertz range. They can therefore be easily observed using a FP etalon. Such an analyzing scheme is shown in Fig. 6. The free spectral range of the FP was 50 GHz so that its finesse of 1000 resulted in a 50 MHz resolution, enabling the sidebands to be clearly resolved, as shown in Fig. 7.

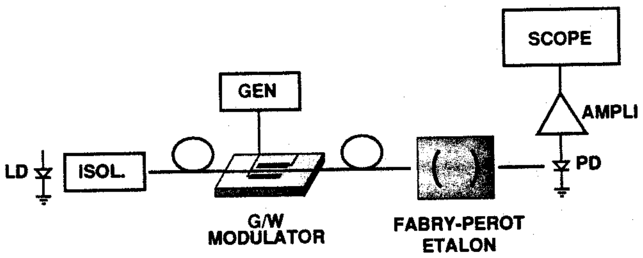


Fig. 6: Schematic diagram of the experimental setup for bandwidthmeasurements using direct optical spectrum analysis of the modulated signal.

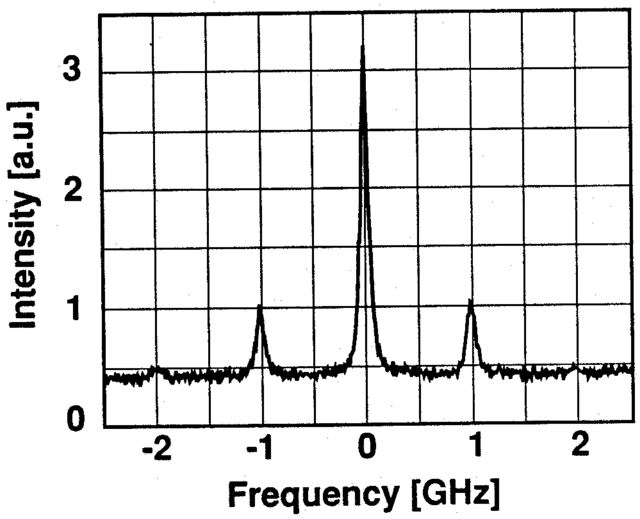


Fig. 7: Optical spectrum of a modulated optical signal measured using a Fabry-Perot analyzer.

The bandwidth can then be measured by sweeping the frequency of the signal driving the modulator and by observing the decrease in the sidebands amplitude. Though it is very accurate and gives an unbiased information of the actual effect of the modulator on the light wave, this technique requires a tunable microwave generator which covers the full investigated frequency range. An alternative way is to drive the device with short electrical pulses. This

can be done by using frequency comb generators, where a continuous electrical signal passes through a set of step-recovery diodes. The resulting comb spectrum, which corresponds to repetitive 130 ps FWHM pulses, consists of discrete lines up to and beyond 18 GHz. In this case the Fabry-Perot directly yields the frequency response of the modulator.
The detection bandwidth is obviously not a limiting factor and can be arbitrary reduced. In addition to the actual representation of the light wave spectrum, this technique has the further advantage to be relevant for any kind of modulator (phase, intensity) without additional optical circuitry. The only requirement is related to the source spectrum, which must be narrow and single-mode. This condition requires the laser source to be isolated, that is, protected against reflected light feedback into the laser resulting in a chaotic spectral behavior.

5. The optical sampling technique

The sampling technique, which relies upon the well-known stroboscopic effect, provides a replication of a high-speed periodic continuous-time signal in an arbitrary enlarged time scale. This can be used to shift an arbitrary optical signal modulated by a guided-wave device down to the low-frequency range [9]. The periodic optical wave form with a repetition rate f_o, launched into the electro-optic modulator, can be described by its Fourier serie:

$$P_{in}(t) = \sum_{j=0}^{\infty} a_j \cos(2\pi j f_o t) + b_j \sin(2\pi j f_o t) = \sum_{j=0}^{\infty} p_j \cos\left(2\pi j f_o t + \phi_j\right)$$

where p_j is the optical power in the j^{th} harmonic of the fundamental frequency f_o.

Besides, the electro-optic is also driven by a periodic electric signal, whose repetition rate is f_m. Whatever the dc bias voltage is, the time dependent power transfer function of the modulator can also be described by its Fourier serie.

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

Therefore, the optical signal output from the electro-optic modulator is given by the product of the input power by the transfer function.

$$\begin{aligned} P_{out}(t) &= \sum_{i,j}^{\infty} h_i p_j \cos\left(2\pi j f_o t + \phi_j\right) \cos(2\pi i f_m t + \varphi_i) \\ &= \frac{1}{2} \sum_{i,j}^{\infty} h_i p_j \left[\cos\left(2\pi (j f_o + i f_m) t + \phi_j + \varphi_i\right) + \cos\left(2\pi (j f_o - i f_m) t + \phi_j - \varphi_i\right)\right] \end{aligned}$$

We can manage to set the two frequencies f_o and f_m very close, $f_m = f_o - \Delta f$, that yields:

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

If the bandwidth of the detector is much smaller than the frequencies f_o or f_m, the high frequency components will be completely averaged out, so that only low frequency components will dominate the time dependent detected output signal:

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

In the optical sampling technique, when used as a high-speed periodic signals analyzer, either the optical signal or the modulation function can be approximated by an impulse function. For instance, when the optical signal is a very short pulse whose duration is much smaller than its repetition time $1/f_o$, all coefficients p_j are close to unity. Convertibly, 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_o, only the terms for $j = i$ will fall within the detector bandwidth, and the AC part of the detected signal will be given by

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

where g is an arbitrary constant which includes the detector sensitivity, the electro-optic attenuation, etc. This means that the detected signal is a replication of the initial optical signal with a frequency shifted from its initial value f_o down to the beat frequency: $\Delta f = f_o - f_m$, as shown in Fig. 8.

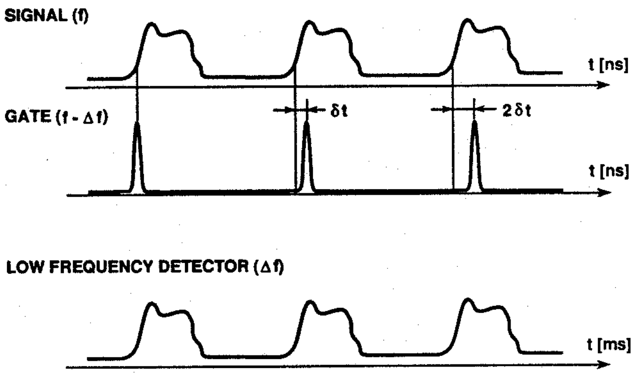


Fig. 8: A short optical gate is used to sample an arbitrary optical waveform, which is replicated in the low-frequency domain.

When using two impulse train signals, this technique can be used to carry out the frequency response of optical guided-wave modulators. Short optical pulses act as an optical probe to analyze an optical gate constituted by the intensity modulator driven by an electrical impulse train signal. The processed signal is then detected by a low-frequency detector. Both optical and electrical signals must have a close repetition rate so that all harmonics of the beat signal in the low-frequency domain are within the bandwidth of the low-frequency detector. Therefore the detected signal is bandlimited only by the modulator, as schematically represented in Fig. 9.

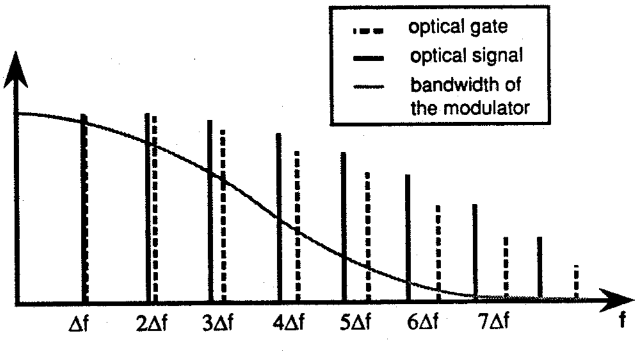


Fig. 9: Frequency representation of both the electrical and optical signals with the modulation bandwidth of the modulator. These two signals give rise to a beat signal with base frequency Δf.

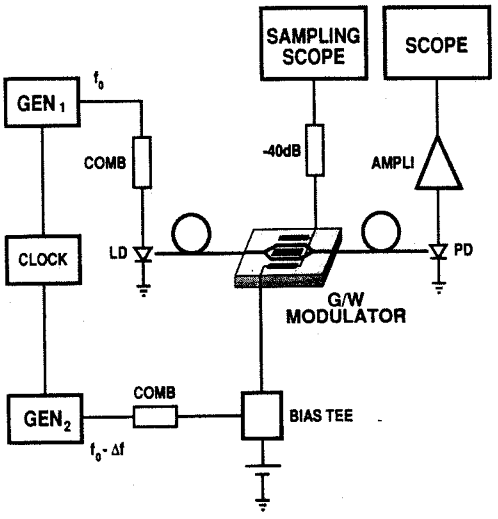


Fig. 10: Experimental setup used for optical sampling.

The experimental setup is schematically shown in Fig. 10. A 10 MHz master clock is used to drive two RF generators at frequencies *f* and *f–Δf*. The impulse trains are produced electrically by frequency comb generators to drive the laser and the modulator. The beat frequency *Δf* is chosen to be 100 Hz, which is 10^6 smaller than the original RF frequency *f*. A 1.3 μm semiconductor laser operating in gain switched condition delivers 50 ps FWHM optical pulses, which are launched into an electro-optic modulator. The output signal is detected by a InGaAs pin photodiode followed by a high gain operational amplifier fixing the bandwidth of the detection system. By using a low-frequency electrical spectrum analyzer the frequency response of the modulator is obtained by analyzing the spectrum of the output signal and knowing the scale factor. Figure 11 presents a typical frequency response of a $LiNbO_3$ electro-optic modulator measured using this method. The resolution depends only on the frequency difference *Δf*, which can be chosen arbitrarily low. In this configuration, the short optical pulses can be used to probe the transfer function of the modulator in the time domain. Figure 12 shows the optical gate actually making the transfer function of the electro-optic modulator. The measured gate width is approximately 115 ps, which corresponds to a switching time less than 100 ps. In the figure, the upper scale represents the effective time scale, whereas the lower shows the time scale in which the measurement was performed.

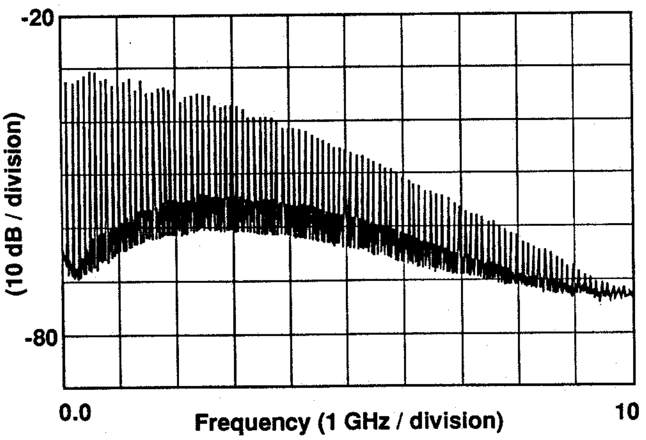


Fig. 11: Typical frequency responce of a traveling wave modulator measured using the optical sampling technique.

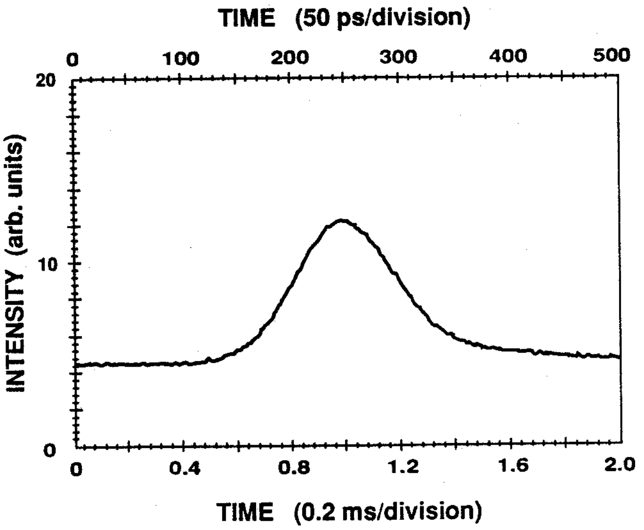


Fig. 12: Measurement of the optical gate generated by the intensity modulator, using the optical sampling technique.

6. Conclusions

Bandwidth characterization of guided-wave modulators with a good resolution can be easily achieved using optical sampling or direct analysis of the modulated optical signal. These methods present the great advantage that the measurements can be performed over a several gigahertz frequency range without using microwave instrumentation and measuring apparatuses. Furthermore, the optical processing translates the relevant information in the low-frequency range, resulting in the use of noiseless and low-cost detection scheme and a standard accurate measuring instrumentation. However, the only limiting factor remains the generation of short electrical pulses, which fixes the maximum measurable bandwidth to approximately 15 GHz. In the case of direct analysis of the modulated optical signal using a Fabry-Perot etalon, there is no limitation provided that a microwave generator with a bandwidth as high as the modulator under test is available.

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