Integrated Optic Devices for Microwave Applications

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(Invited Paper)

Abstract — Integrated optic devices designed for use in microwave applications are reviewed and the prospects for these new technologies are discussed. The interaction of lightwave and microwave signals, especially the modulation of light at microwave frequencies, is briefly summarized, and features of integrated optic devices are pointed out.

I. Introduction

RECENTLY much attention has been given to research fields where light and microwave signals are related to each other. The high-bit-rate lightwave transmission system is one example. Even in the early stages of optical electronics, however, the interaction of light and microwave signals was an attractive problem. The reason for this is the potentially large bandwidth when the lightwave is used as a carrier. Nevertheless, the relation between light and microwave signals has not had practical application until quite recently, when various high-speed optical devices, especially excellent integrated optical components, have become available.

In this paper, the interaction of lightwave and microwave signals, especially the modulation of light at microwave frequencies, is briefly discussed, and integrated high-speed devices and their applications are described.

II. Light and Microwaves

The most interesting aspect of the light–microwave relation is the interaction of these two waves. The use of microwave signals for the fast control of light is an important technique. High-speed light modulator/switches have been successfully developed [1]. The frequency, or the photon energy, of lightwaves is some ten thousand times higher than that of microwaves; thus controlling a lightwave signal is very difficult compared with controlling a microwave signal. The use of light to control microwave devices is another important feature of the light–microwave interaction. A few examples will be given in the later part of this paper. Owing to the excellent transmission properties of optical fibers and the rapid development of optoelectronic devices, lightwave technologies are being introduced into microwave systems. Other important features of using lightwaves for the control of microwave signals are the possibilities of realizing shorter response times and higher isolation between controlling and controlled signals. Intensive research in these fields has already been started.

At the first stage of these applications, a directly modulated semiconductor laser may be utilized in combination with a single-mode optical fiber and a photodiode receiver. Direct modulation, however, presents several problems for applications, such as the limitation of modulation frequency (around 20 GHz now) and the unavoidable combination of intensity and frequency modulations in the modulated laser output. Therefore, to realize higher performance at high frequencies and more complicated functions, it is desirable to introduce external devices for processing the lightwave signals, that is, the use of optical waveguides formed on a planar substrate. Optical devices based on this idea are called guided-wave optical devices. Integration of these devices on a substrate leads to the concept of integrated optical circuits, which was introduced at the end of the 1960's [2], [3]. Guided-wave optical devices have several merits, such as compactness, stability, possibility of integration, and convenience of connection with single-mode fibers.

One of the most important features is that much higher performance can be obtained with guided-wave devices than with ordinary, bulk-type devices. For an electro-optic modulator of the waveguide type, for instance, the $P/\Delta f$ (i.e., modulating power/bandwidth) figure is 10^{-2} to 10^{-3} times less than that of ordinary, bulk-type modulators and their operation bandwidth extends now up to 40 GHz, a level quite difficult to achieve by using the bulk-type structure.

It might also be interesting to note significant differences in the structure and operating mechanism of the optical element from its microwave counterpart. An example is the optical waveguide Y junction, which is a well-known and widely used guided-wave circuit element. Two single-mode branch waveguides are merged into a stem waveguide which also supports only the fundamental mode. The branching angle is usually taken very small, around 1/50 or 1/100 rad, in order that the propagation mode may be adiabatically transformed from the eigenmode at the input side to the other eigenmode of a different waveguide system at the output port. If this Y branch were designed for operation at microwave frequencies (using

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dielectric waveguides), a junction of several meters might be required to obtain a separation of a few centimeters. For the optical waveguide, however, sufficient separation, say 10 or 20 μm, can be achieved with a junction length of about 1 mm. At first sight, the circuit element looks like a lossless three-port. Its operating mechanism, however, can be explained only by considering the loss associated with the radiation mode excited at the junction as a fourth port [4]. This loss can occur because the optical waveguides are not metallic hollow guides but rather dielectric.

$LiNbO_3$ is now the most widely used waveguide material. It has large electro-optic, acousto-optic coefficients and also exhibits nonlinear optic effects. The waveguide is usually formed on the crystal surface by Ti indiffusion, or H^+/Li^+ ion exchange. The fabrication conditions which give good propagation and modulation performance, low coupling loss to fibers, and a wide range of temperature stability have been investigated intensively.

Semiconductor materials have also rapidly developed as waveguide materials. Compound semiconductors such as GaAs or InP will be especially important for integrating waveguides, sources, and detectors on the same substrate, and also for integrating optical and electronic elements, as in optoelectronic integrated circuits (OEIC's).

Further details on optical guided-wave devices and integrated optics can be found in certain books, such as [5]–[7].

III. Microwave Control of Lightwaves

A. Light Modulation in Microwave Range

Although the direct modulation of laser diodes is a simple and convenient method for generating a modulated lightwave, external devices designed specifically for the modulation/switching of lightwaves by microwave and millimeter-wave signals are important in order to obtain a reliable, high-performance system.

In many cases, the modulators/switches operate by using the electro-optic effect. The refractive index changes in proportion to the applied modulating electric field without power consumption, in principle, and also responds fast enough to millimeter- or submillimeter-wave signals. With the linear electro-optic effect, phase modulation is achieved simply by placing a pair of parallel electrodes on both sides of a straight optical waveguide. For an $LiNbO_3$ waveguide, it is not difficult to achieve a 1 rad phase modulation with a drive voltage of 1 or 2 V. To realize intensity modulation or switching, an interferometer or a directional coupler structure is used as an optical circuit of the device.

A powerful way to increase the modulating frequency to the microwave region is the use of a traveling-wave mode of operation not only for the conventional bulk-type but also for the guided-wave modulators [8]. The modulating microwave propagates in the same direction as the lightwave on the parallel coplanar electrodes. The electrode as a part of wide-band microwave circuits became important. To avoid the unwanted coax-to-coplanar discontinuity effect an asymmetric coplanar stripline [9] was successfully used. The three-electrode coplanar line was also introduced as an effective electrode [10].

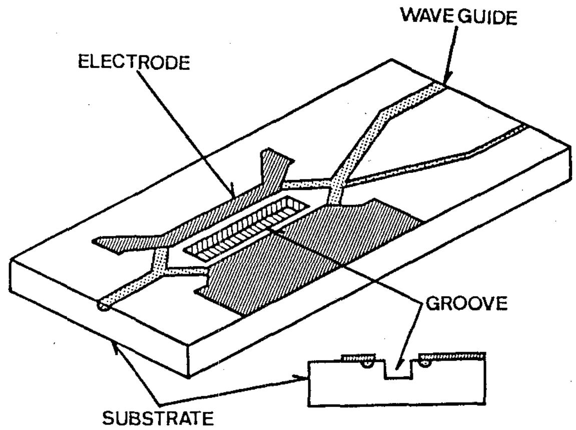

Fig. 1. Traveling-wave Mach–Zehnder light intensity modulator with an etched groove [11].

B. Improved Traveling-Wave Operation

For most practical guided-wave modulators, the velocities of the lightwave and the microwave are not matched with each other, and their bandwidths are limited by the velocity mismatch. With a reduced interaction length L, faster operation will be achieved, although higher drive power is required since the power is proportional to $1/L^2$. A method to realize efficient and fast, or wide-band, operation at the same time is to reduce the velocity mismatch between light and modulating waves. For $LiNbO_3$ waveguides with coplanar electrode, the lightwave travels about twice as fast as the modulating microwave, so the velocity of the lightwave must be decreased and/or that of the microwave must be increased.

In a typical example, shown in Fig. 1, a groove is provided between the parallel electrodes of the coplanar asymmetric stripline in order to speed up the modulating wave [11]. The groove also decouples the two parallel optical waveguides composing the Mach–Zehnder interferometer, thereby reducing the electrode separation or the modulating voltage needed. A very high sensitivity, $P/\Delta f = 1.5$ mW/GHz, and an 11.5 GHz 3 dB bandwidth were obtained at 633 nm. Fig. 2 shows another example: the use of a shielding ground plane above the coplanar strip on the $LiNbO_3$ substrate [12]. With this structure, efficient modulation was performed over 20 GHz. The velocity mismatch is also reduced by using an extremely thick (7 to 9 μm) electrode [13]. The attempt to achieve perfect velocity matching is also pursued for the $LiNbO_3$ modulator using the ridge waveguide structure [14]. Periodic loading of the capacitance between modulator electrodes has been used to form a slow-wave structure for the GaAs traveling-wave modulator [15] wherein the modulating wave is faster than the light wave.

Another approach for realizing efficient broad-band modulation is the sequential reversal (aperiodic or coded reversal) of the modulation polarity by, for example, shift-

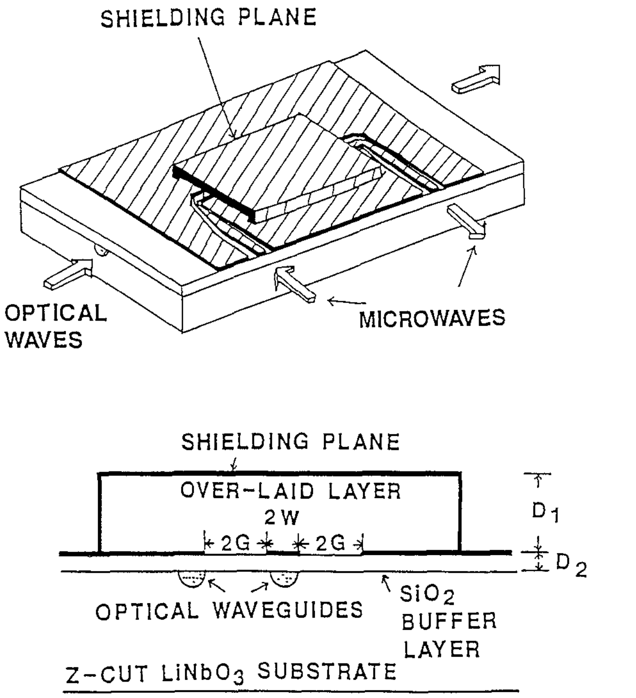

Fig. 2. Traveling-wave modulator using a coplanar strip electrode with shielding over plane [12].

ing the position of electrodes relative to the optical waveguides [16]. The scheme was initially applied to the bulk-type modulator [17]. The phase difference between the electrical and optical waves which builds up during their propagation with different velocities is canceled out at certain traveling distances by the inversion of modulation polarity. Applying a special sequence for the reversal (instead of a periodic one) of the modulation polarity can result in broad-band operation; bandwidths up to 40 GHz have been reported [18].

C. Band Operation

As a different way to achieve light modulation in a higher frequency range, the use of band operation has been studied. In the case of usual baseband operation, a wider bandwidth will be needed to modulate the lightwave at higher frequencies since the lower end of their operation band reaches zero frequency. The band modulation scheme reduces the drive power dramatically at the expense of narrowing the bandwidth to within bands around several center frequencies. The concept of band-limited modulation will play an important role in future optoelectronics systems.

Fig. 3 is an example of the band modulator using the resonant electrode [19]. The device was built and operated successfully from 33 to 40 GHz with a phase modulation depth up to 1.5 rad. In the same figure, the observed frequency response is shown for the input power leveled at 220 mW. The 3 dB bandwidth was around 5 GHz centered at 35.3 GHz and the required power for 1 rad phase modulation was 450 mW. The modulation experiment was also carried out at the fundamental resonance, 17 GHz, of the electrode, instead of the second resonance at 35 GHz, to have a 2.2 rad phase modulation with 220 mW drive power.

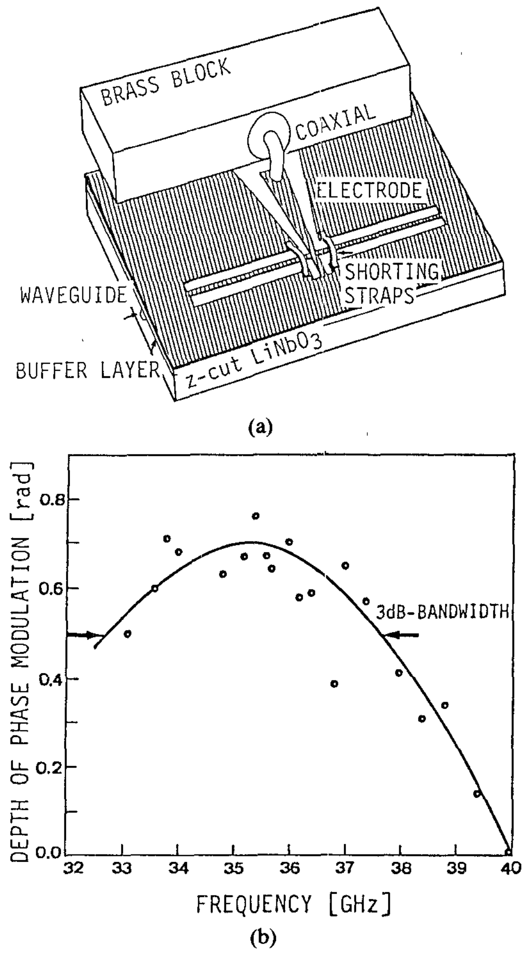

Fig. 3. (a) The guided-wave band modulator using resonant electrode structure and (b) its frequency response [19].

The band operation has occasionally been applied for bulk-type modulators by placing the electro-optic crystals in electrical or optical resonators, while for waveguide modulators it was initially proposed use a periodic polarity reversal scheme [20], and was realized by using a standing-wave electrode structure [21]. Recently, they have also been constructed by using the method of periodic reversal of modulation polarity [22], [23], and the electrode of fast-wave structure [24] loading inductances periodically between parallel electrodes both for $LiNbO_3$ traveling-wave modulators.

IV. Integrated Optic High-Speed Devices and Their Microwave Applications

One of the most important features of guided-wave devices is the possibility of realizing integrated optical circuits. Integration of high-speed guided-wave components on a single substrate provides compact and stable optical circuits which enable us to construct novel optoelectronic functional devices.

Switch matrices composed of multiple optical switch elements have attracted attention for use in space-division switching in optical communication systems, and a good

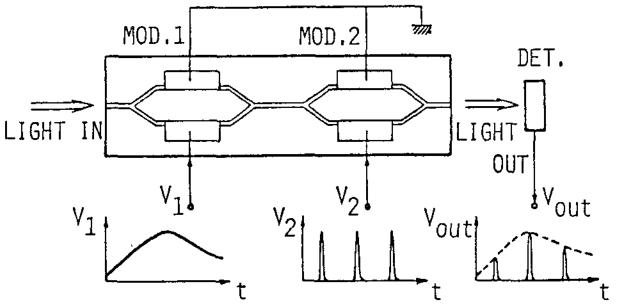

Fig. 4. Integrated tandem light modulators [31] and the working mechanism of signal multiplication.

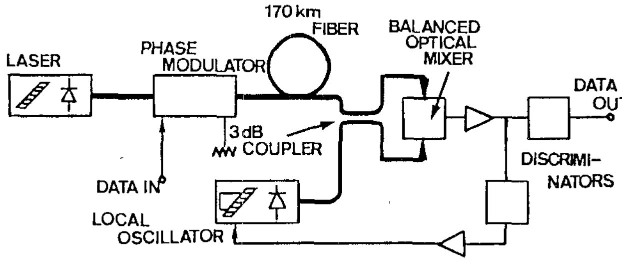

Fig. 5. Coherent light transmission at 2 Gb/s using phase modulation [32].

deal of work has been reported [25]. Although each element is a rather low speed switch, lightwave signals modulated at microwave frequencies can be handled. For the integration of high-speed devices, however, only a few examples have been reported because of difficulties in integration. Examples are a SSB modulator/frequency shifter [26], a signal sampler/multiplier [27], a time multi/demultiplexer [28], an analog-to-digital converter [29], and a spectrum analyzer [30].

As shown in Fig. 4, the signal sampler/multiplier consists of the tandem integration of two guided-wave interferometer modulators. The circuit has one optical and two electrical input terminals. Various kinds of correlation between signals from these inputs are obtainable with this device. For example, by applying a fast electrical pulse train to modulator #2, sampling of the fast electrical signal applied to modulator #1 can be performed with an input CW light signal. An actual device was constructed on a $LiNbO_3$ substrate, and a 2 GHz CW signal sampling experiment was successfully carried out using a fast electrical pulse train of 1 GHz repetition rate from a comb generator.

Application of integrated optic devices and components to various microwave systems is a promising area. Recent rapid progress in integrated optics technologies urges us to evolve possible new applications and to evaluate their feasibility, although only a limited number of examples have been reported.

Recently high-speed guided-wave light modulators have been successfully used for experimental high-bit-rate transmission systems. A 12 Gb/s transmission system over 100 km was constructed using a $LiNbO_3$ intensity modulator and tested with success [31]. As shown in Fig. 5, the application to the coherent lightwave communication system [32] is also interesting, since the optical frequency of a semiconductor laser tends to vary during high-frequency amplitude modulation. High-speed time-multiplexed digital transmission is another example; an 8 Gb/s system was demonstrated by multiplexing two 4 Gb/s subsystems [33].

The guided-wave transmission of analog microwave signals is also important. To deliver microwave or millimeter-wave signals from one place to a distant place, a lightwave can be modulated by the RF signal and transmitted to its destination over low-loss optical fiber. In an example of a link [34], a 10 GHz CW signal was transmitted by using an $LiNbO_3$ waveguide traveling-wave modulator, with a 1.3 μm CW laser, an optical isolator, a 1 km single-mode fiber, and a high-speed InGaAs photodiode.

Endeavors to realize stable, low-noise, and/or multifrequency lightwave sources are also being pursued utilizing integrated optics. The 3 GHz sinusoidally modulated optical output of a Mach–Zehnder modulator was used to injection lock a DFB laser diode, which in turn generated AM sidebands [35]. It is also interesting to use integrated optic modulators for the mode locking of semiconductor lasers to generate optical pulse trains [36]. An integrated optical eight-port 90° hybrid was fabricated and tested for use in a balanced phase diversity receiver for heterodyne reception [37]. Another interesting example is the application to optical signal distribution for the scanning of array antennas [38], [39].

Measurement is another field of interest. For example, the combination of optical fiber and a high-speed modulator could be used to measure the field distribution of microwave devices, from MIC's [40] to the antenna [41], with minimum field disturbance. Precise measurement of the distance (a range finder) is also a promising application of integrated optics. Guided-wave fast light modulators/switches are now going to be used in optical test instruments, such as optical time-domain reflectometers (OTDR's) and lightwave component analyzers. Introduction of integrated optics technologies to microwave elements, for example optically tuned Gunn oscillators and optically controlled MIC couplers [42] and phase shifters/attenuators, will also be important.

V. Conclusion

Integrated optic devices designed for use in microwave applications were reviewed and the prospects for these new technologies were discussed. A number of possible applications have been proposed and investigated, while a few practical devices have been implemented. With the recent growing interest in this area, we can expect rapid development in the utilization of lightwave technologies in microwave engineering.

We have come to the point where the next target is the interaction between lightwave and millimeter-wave signals. Several attempts have already been started to devise fast optoelectronic devices such as millimeter-wave light modulators and fast optoelectronic signal samplers. Utilization of the lightwave interaction with submillimeter waves and even with lightwaves will be a natural direction in the future.

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