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Resonant modulation

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Devices that offer fast modulation and switching of light waves currently attract widespread research efforts for potential applications in high-speed signal processing. The guided-wave techniques of integrated optics have demonstrated the capability to achieve drive power/bandwidth levels of a few milliwatts per gigahertz modulation bandwidth. Most recently, efforts have been concentrated on electro-optic travelling-wave configurations (Alferness *et al.* 1983; Gee & Thurmond 1983; Cross *et al.* 1984) to achieve operation at higher frequencies with higher bandwidths than are usually obtainable from lumped-electrode devices, wherein the dominant restriction of the speed of operation is the *RC* constant associated with electrode charging and discharging. Here, we discuss the potential merits of an alternative approach, which employs resonant optical waveguide cavities.

Electrical power supplied to an electro-optic waveguide modulator is generally lost, although it is not necessarily dissipated in the modulation process itself. A reduction in the power that must be supplied is clearly attractive in itself and, through thermal considerations, becomes almost essential when closely packed devices are considered. In practice, the reduction amounts to an improvement in the modulator response. It can be achieved by reducing (i) the interaction volume, (ii) the electrical bandwidth or (iii) the optical bandwidth. In adopting the integrated optical approach, the first step is essentially taken in the direction indicated by (i). However, there remains scope for further improvement by several orders of magnitude, theoretically, over the performance demonstrated by currently favoured device geometries. In figure 1 we indicate possible directions for improvement achievable in a simple electro-optic phase modulator by following (ii) and (iii).

Reduction of the electrical bandwidth can be accomplished by introducing an electrical resonator into the structure (Molter-Orr *et al.* 1983), assuming, of course, that the device is not required to operate at d.c., which is the case in many of the applications envisaged. The electrical, modulating field for a given input power is thereby increased in proportion to the Q-factor of the resonant cavity. Alternatively, we may choose the approach indicated by (iii) above and reduce the *optical* bandwidth of the device, and here the gains are potentially very much greater.

The waveguide phase modulator can be placed within a Fabry–Perot cavity, as shown in figure 1, with reduction in the optical bandwidth according to the finesse of the cavity. Such an optical waveguide resonator containing an electro-optic element has been used to form a hybrid bistable optical device wherein feedback is derived from an optical detector monitoring the cavity throughput (Smith *et al.* 1978). If, however, the feedback loop is disconnected and the resonator and active element is considered independently as a modulator, the cavity can be seen to perform two functions. First, the applied phase (delay) modulation is converted to

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an intensity modulation: this is well known and is readily performed in other, arguably superior ways. Secondly, the cavity enhances the modulation for a given drive power by a factor of the order of the Q-factor of the resonator. But it is significant to note that this applies to phase modulation as well as amplitude modulation: indeed, in this device phase modulation is generally more convenient, since the accompanying gain is maximal on the resonance peak and is in the same sense throughout.

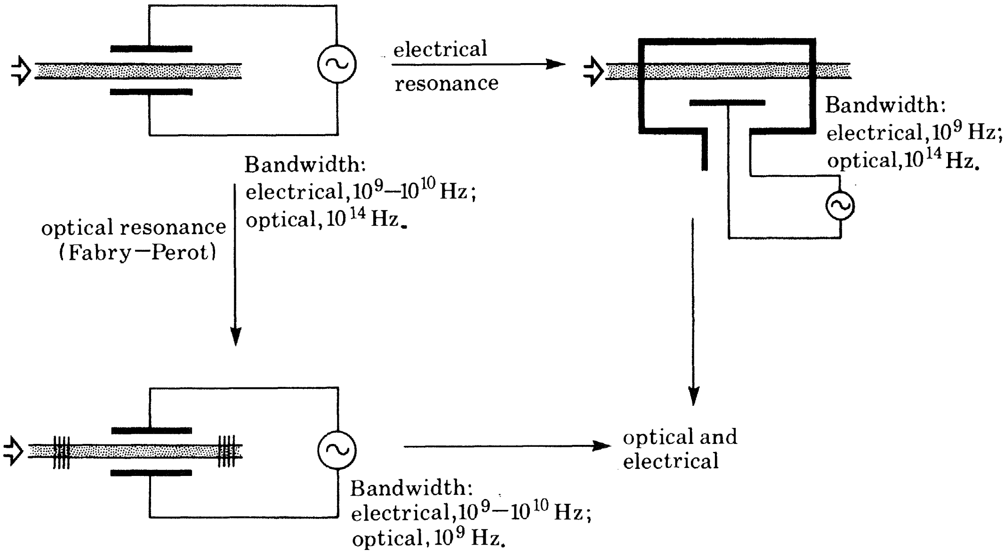

FIGURE 1. High-speed electro-optic phase modulation.

The foregoing arguments are most significant for high-speed modulation of an optical wave, permitting considerable gain enhancement to be achieved without reducing the overall modulation bandwidth to r.f. levels. This gain would generally be accessed by reducing the size of the device. Higher modulation frequencies can be achieved by driving the device between successive cavity resonances, as indicated by figure 2, achieving an unrestricted frequency range

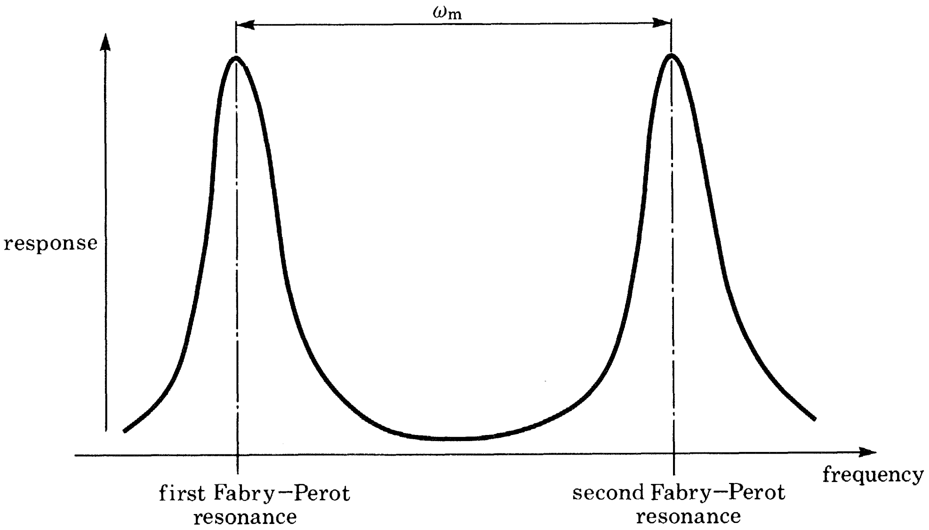

FIGURE 2. Phase modulation at frequency ω_m by sweeping through successive Fabry–Perot resonances.

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with limited, but still large, modulation bandwidth. By reducing the optical bandwidth from 10^{14}–10^{15} Hz to that actually required, there is an obvious potential gain amounting to several orders of magnitude.

Several configurations might be adopted for the resonant waveguide phase modulator including Fabry–Perot and distributed feedback resonators, and the ring resonator. It is worthy of note that in those resonators exhibiting multiple resonance peaks the gain in sensitivity is reduced . In this context, the use of a distributed feedback resonator demonstrating a simple sharp resonance may be preferable, although clearly over-restriction of the bandwidth will impose severe tolerance requirements on the stability and control of the optical source linewidth.

We have achieved qualitative confirmation of the principle described by employing electro-optic waveguides formed by thermal diffusion of titanium into $LiNbO_3$. By using the Z-cut crystal orientation, waveguides supporting a single mode at a (free-space) wavelength of 1.15 μm were prepared. The ends of the crystal were carefully cut and polished normal to the waveguide axes and the resonator was formed by cementing multilayer dielectric mirrors to these ends. The drive voltage was applied to electrodes deposited on the crystal, separated from the waveguides by an isolating layer of SiO_2. Figure 3 shows a test device mounted on a carrier, which supplies the drive signal to the electrodes via a terminated microstrip line. The test devices were less than ideal, exhibiting finesse of only 4–5, ascribable largely to optical losses at the cemented mirrors. However, application of an alternating voltage of increasing frequency appears to confirm the principle described, and new higher finesse devices, which we are now preparing, are expected to demonstrate the effect fully.

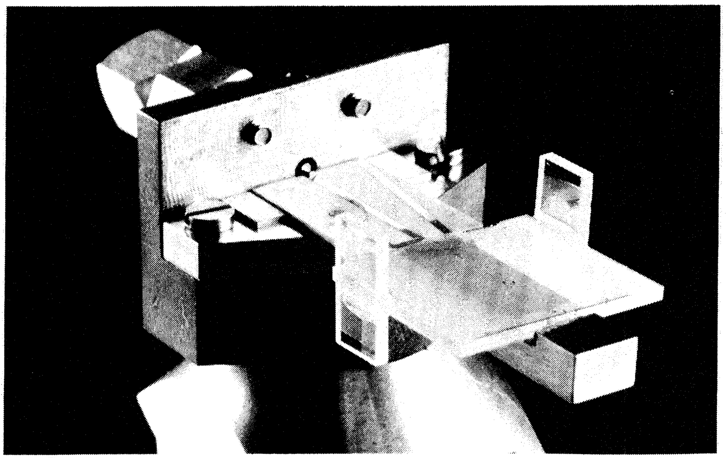

FIGURE 3. Experimental waveguide electro-optic resonant modulator in Ti:$LiNbO_3$.

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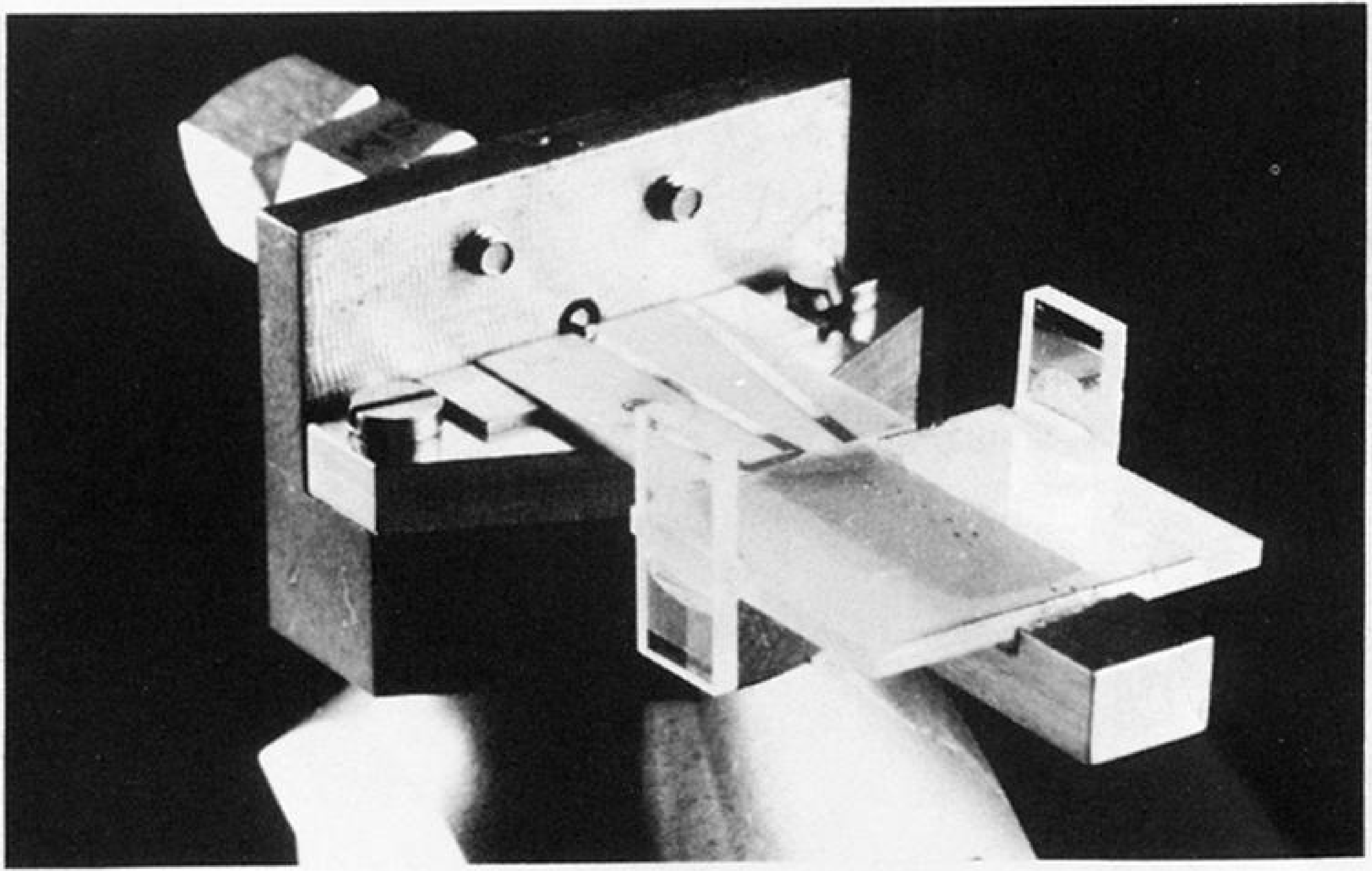

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