Integration of High-Speed Optical Taps with InP Waveguides

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Abstract—**Optical taps are key elements for optical signal processing. We demonstrate the high-speed operation of an InGaAs p-i-n photodetector on InP waveguides. For a 300 μm long tap that samples 19 percent of the light propagating in a 7 μm wide waveguide, the response time is 50 ps at a 1 V reverse bias. The taps require a single epitaxial growth and can readily be integrated with electrooptic modulators and other optoelectronic devices for multigigahertz optical signal processing.**

PLANAR optoelectronic integrated circuits that switch or process light propagating in optical waveguides are attractive because of their potential for high-speed operation. A key element for such circuits is a high-speed optical tap that samples a small part of the light in a waveguide and converts it to an electrical signal while allowing most of the light to continue through for further signal processing. The electrical output of the optical tap may, for example, detect the address bits in a data packet and set downstream optical switches to route that packet accordingly. Accomplishing such complex signal processing at high speeds requires the additional integration of modulators and transistors. We report here the realization of a 7 GHz optical tap in the InP/InGaAs material system employing an epitaxial structure that allows further integration of electrooptic modulators and ion-implanted field-effect transistors [1].

The epitaxial structure consists of a homojunction u/n$^+$ InP waveguide with InP–InGaAs single heterojunction p-i-n photodiode layers on top (Fig. 1) grown by low-pressure organometallic chemical vapor deposition on an n$^+$ InP substrate. The structure consists of a 3.5 μm undoped InP guiding layer, a 0.3 μm p$^+$ ($N_A \sim 2 \times 10^{18}$ cm^{-3}) InP layer, a 0.5 μm undoped $In_{0.53}Ga_{0.47}As$ absorbing layer (with a background doping of $N_D \sim 1 \times 10^{15}$ cm^{-3}), and a 0.2 μm n$^+$ $In_{0.53}Ga_{0.47}As$ contacting layer. Because the photocurrent does not traverse the InP guiding layer [2], [3], high-speed performance does not degrade with increased guiding layer thickness, permitting a thick guiding layer which facilitates input and output coupling. The p–InP layer, in addition to serving as an electrode for the photodiode above, can also serve as an electrode for the electrooptic modulator below. The tap does not require epitaxial regrowth [4] or growth on nonplanar substrates [2].

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We form waveguide ribs by selective chemical etching of the InGaAs layers and Ar ion milling 1.1 μm of the InP. These ribs are 7μm wide far away from the taps and 13 μm wide at the tap, with the transition occurring gradually over 300 μm to minimize the effects of modal mismatch. We next etch the InGaAs to delineate taps that are 300, 500, and 1000 μm long and 7 μm wide, leaving a 3 μm wide p–InP ledge on either side for electrical contacts. The p–InP layer is removed by Ar ion milling everywhere except where needed for ohmic contact leaving 0.8 μm high waveguide ribs away from the taps. Contacts are made to the p–InP along the ledges to minimize parasitic resistance and to the n–InGaAs cap along the top of the tap (Fig. 1). A polyimide insulating layer and Ti/Au final metal are then added to complete the device fabrication.

The transmitted light power P_{out} and the photodetector current i_{ph}, which are linear with the input power P_{in}, were measured using a CW λ = 1.32 μm laser. The response at P_{in} = 1 mW for the three tap lengths on 2000 μm long cleaved waveguides is shown in Fig. 2. These are fitted to

$$P_{out} = \frac{T_i T_0 e^{-\alpha L} P_{in}}{1-(1-T_0)^2 e^{-2\alpha L}} \quad (1)$$

$$i_{ph} = \frac{T_i Q (1-e^{-\alpha L}) P_{in}}{1-(1-T_0) e^{-\alpha L}} \quad (2)$$

where T_i is the input coupling coefficient, T_o is the output coupling coefficient, α is the absorption coefficient of the tap, L is its length, and Q is the quantum yield. The denominators account for multiple reflections, which add incoherently because of the multimode source, within the cavity formed between the cleaved waveguide facets. These equations assume all loss to be in the tap itself and neglect any internal reflections. Taking $Q = e\lambda/hc$ = 1.06 A/W and $T_o = 1 - (n-1)^2/(n+1)^2 = 0.726$ where n is the InP index of refraction, the analysis yields $T_i = 0.25 \pm 0.01$ (−6.0 dB) and $\alpha = 5.2 \pm 0.5$ cm^{-1} (−22.5 dB/cm). The portion of T_i due to modal mismatch is T_i/T_o = 0.34 (−4.6 dB). This value for α is consistent with previous predictions [5]. Using an absorption of $\sim 10^4$ cm^{-1} for InGaAs gives a power filling factor on the order of 10^{-3}. For tap lengths of 300, 500, and 1000 μm, the internal quantum efficiencies $i_{ph}/T_i Q P_{in}$ are 19, 29, and 47 percent, respectively.

We determined the pulse response of the taps to 1.3 μm wavelength light using a comb generator and a laser diode producing ~50 ps FWHM pulses. The input light was end-

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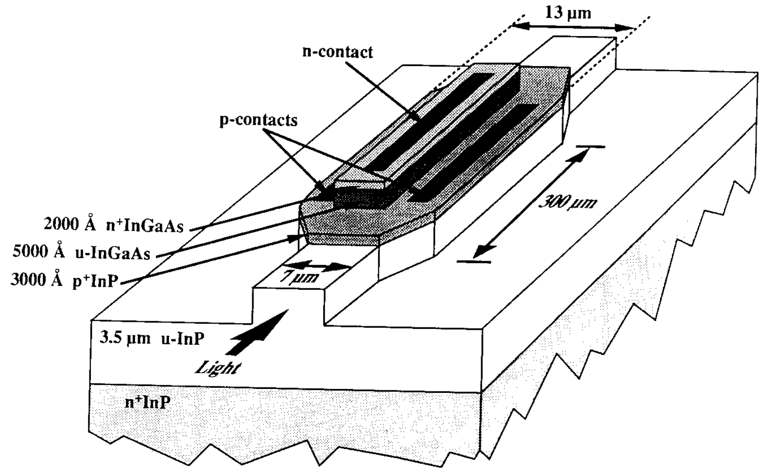

Fig. 1. Schematic of the optical tap (not to scale). For clarity, the polyimide insulating layer and the final metal are omitted and the waveguide taper is greatly exaggerated.

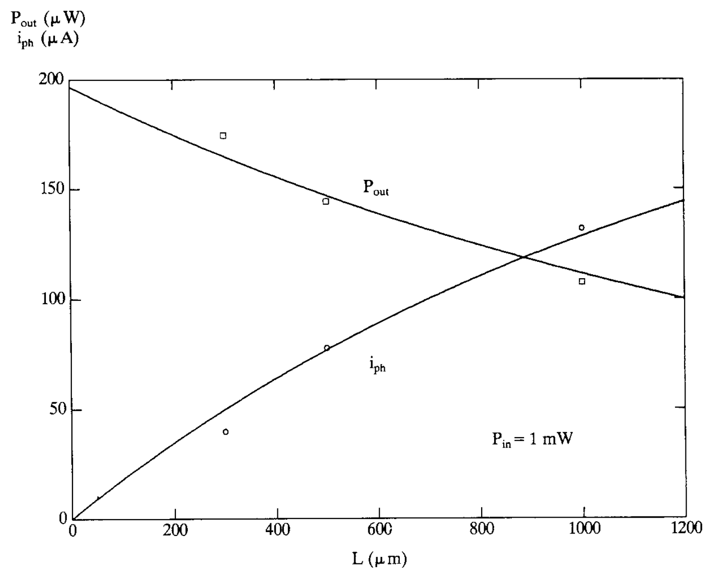

Fig. 2. Output current and transmitted light power as a function of tap length at P_{in} = 1 mW. Lines are based on the least square analysis discussed in the text.

fire coupled into the waveguide and the tap was electrically probed with a 26 GHz Cascade high-frequency probe head on a special mount. The response was measured using a 1 V bias, where the dark current for a 300 μm long device is typically ~70 nA, and did not depend strongly on the bias. The response of the 300 μm long tap under a 1 V reverse bias (Fig. 3) yields a 50 ps time constant after deconvolution. The deconvoluted response times of the 500 and 1000 μm taps are 90 and 150 ps, respectively. Measurements at 100 MHz repetition rate optical pulses reveal no long tail in the pulse response, indicating that carriers do not pile up at the heterojunction.

These response times can be understood in terms of the device resistances and capacitances. An equivalent circuit model for the tap (Fig. 4) consists of an RC transmission line with the series resistance R_n from the n-contact and the shunt resistance R_p from the p-contact. The transmission line shunt capacitance C, from the p-n junction, is charged by the photogenerated carriers and discharges into the load formed by the impedance of the measurement system Z_o = 50 Ω in parallel with the initially uncharged parasitic pad capacitance C_p. The capacitances measured at 1 MHz for the three lengths, 0.89, 1.26, and 2.18 pF, can be modeled by adding a component that scales with the tap length, C = 1.84 pF/mm to one that is constant, C_p = 0.34 pF. The n-contact resistance R_n is measured to be 80 Ω/mm and, from separate transmission line testers, the p-contact resistance R_p is estimated to be 20 Ω-mm with approximately equal contributions from the contact

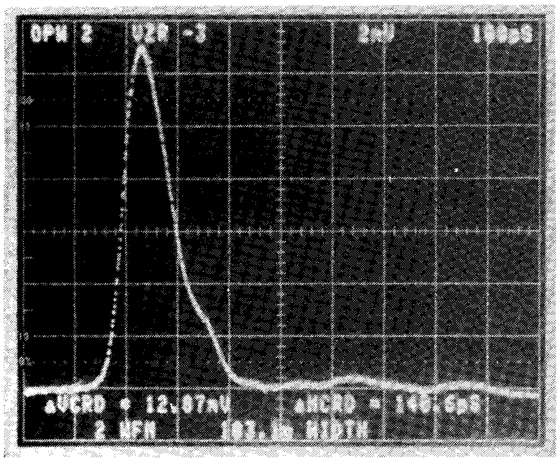

Fig. 3. Pulse response of a 300 μm tap to a ~50 ps FWHM laser pulse. The horizontal scale is 100 ps/div. The deconvoluted response time is 50 ps.

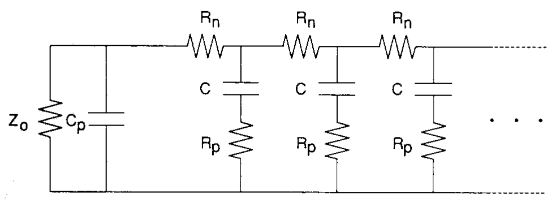

Fig. 4. The equivalent circuit for the optical tap. The light charges the distributed junction capacitance C which then discharges through the distributed resistances R_p and R_n into a load formed by the impedance Z_o of the measurement system in parallel with the pad capacitance C_p.

resistance and the sheet resistance. The time to discharge the transmission line is given by the smallest pole of the equivalent circuit

$$\tau \approx (R_p + Z_0 L + R_n L^2/3)C + R_n L C_p/3 - Z_0 C_p. \quad (3)$$

The last term is negative because C_p equalizes the circuit and speeds the response. With the values given above, we calculate response times of 55, 80, and 170 ps for the three tap lengths. Such close correspondence between measured and calculated speeds indicates the taps are RC rather than transit time limited as expected.

The speed should be significantly improved by decreasing R_p and C. By increasing the p–InP layer thickness to improve the sheet resistance and by using a quaternary alloy to improve the contact resistance, R_p can be lowered. The lower portion of the nominally undoped InGaAs layer appears to be unintentionally p-doped, explaining a 30 percent larger than expected junction capacitance. Increasing the thickness of this layer will decrease the capacitance. Moreover, the coupling of the light from the waveguide to the absorbing region is expected to be stronger [5], necessitating a shorter, and thereby faster, tap to sample a particular fraction of the light in the waveguide.

In conclusion, we have demonstrated the feasibility of InP-based optical taps with several desirable characteristics: high-speed response, low-voltage operation, low-dark current, easy coupling to optical fibers, simple epitaxy requirements, and integratability with other optoelectronic devices such as directional coupler switches needed to process the sampled light. With the implantation of FET's in the thick undoped guiding layer, we envision planar, multigigahertz optoelectronic circuits where an optical signal is sampled and processed according to the information in the signal itself.

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