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# Improved Design of the Coupled-Waveguide Optical Modulator with p-n Junction

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The coupled-waveguide optical modulator/switch (the electrically switched optical directional coupler) will be very important in integrated optics, because it can modulate light intensity directly without any polarization analyzer and can switch light from one waveguide to the other. It was realized for the first time in a form of GaAs device with p-n junction and layered structure as illustrated in Fig. 1<sup>1)</sup>. Design theory of this type of device with p-n junction has been improved and we are reporting in this paper some results, including those on new structures which have GaAs-$Al_xGa_{1-x}As$ heterojunctions or strip-loaded channel waveguides.

The coupling efficiency of optical power from guide 1 to guide 2 in Fig. 1 is modulated by perturbing the phase constant $\beta_1$ of guide 1. Increase in the reverse voltage on the p-n junction causes increase in $\beta_1$ through increase in the width and the refractive index of the depletion layer. The increase of the refractive index is due to the linear electrooptic effect and the depletion of free carriers. Since the situation is rather complicated, a number of numerical analyses on a computer have been carried out so as to minimize the modulating power per bandwidth $P/\Delta f(=Cv^2/2$, C: junction capacitance, v: peak modulating voltage) under various limiting factors such as insertion loss, possible dimensions and carrier concentrations.

Examples of designed GaAs and GaAs-$Al_xGa_{1-x}As$ devices with planar guides are listed in Table I for 1.06 μm light. Some of the important points to reduce $P/\Delta f$ are as follows:

a) In the near-infrared region, $P/\Delta f$ decreases a great deal if one reduces the carrier concentration of layer B $N_B$ so that the depletion layer may cover layer B completely. Modulation is caused mainly by the linear electrooptic effect in this case. An example of computed $P/\Delta f$ is shown in Fig. 2 as a function of $N_B$ (here $n_i$ means refractive index of intrinsic GaAs). For 10.6 μm and longer wavelength light, on the other hand, the depletion effect of free carriers becomes more useful for modulation.

b) $P/\Delta f$ is generally smaller in the case of $n_A > n_C$ than $n_A = n_C$, because the optical field overlaps the depletion layer better.

c) It is usually advantageous when $n_B/n_{A,E}$ and $n_B/n_C$ are increased, as guide width being narrowed correspondingly. By introducing heterojunctions, this condition is attained easier without the increase of insertion loss. Even in heterostructure, $N_B$ should be sufficiently lower than $N_A$ so that the depletion layer spreads mainly to layer B. It should be noted that tolerances in heterojunction devices are severer than those in homojunction devices.

Samples similar to examples (1) and (2) in Table I have just been fabricated. Since their cutoff frequencies are estimated to be higher than 600 MHz for load of 50 Ω, we are now preparing for the modulation experiment of 1.06 μm light at several hundred MHz.

Now we propose a modulator with strip-loaded channel waveguides as illustrated in Fig. 3. Here the light wave is confined not only vertically but also horizontally. Mainly because of smaller capacitance, $P/\Delta f$ is much improved. This device is easier to get synchronism of optical waves in both guides, and is capable of push-pull operation. The electrodes are separated far from the guide layer. This situation is quite different from that in other devices with channel waveguides demonstrated recently$^{2),3)}$ and would be helpful in reducing the insertion loss.

Using the equivalent refractive index method$^{4),5)}$, GaAs devices have also been analyzed on a computer. Some design examples are shown in Table II. The peak modulating voltage for 100 % modulation is about 6 V in example (2'). Layers A and C may be replaced by $Al_xGa_{1-x}As$ layers in these samples.

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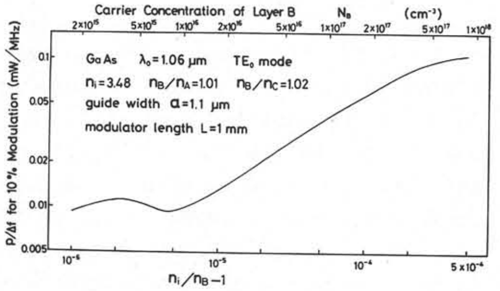


Fig. 2 P/Δf as a function of $N_B$

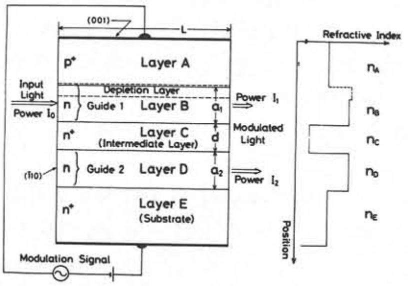
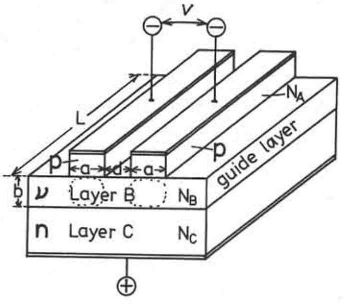


Fig. 1 five-layered planar modulator



$N_{A,B,C}$: carrier concentration

Fig. 3 strip-loaded channel modulator

Table I Design examples of GaAs and GaAs-$Al_xGa_{1-x}As$ planar modulators for 1.06 μm light.
[$TE_0$ mode, horizontal width is 50 μm]

| | (1) | (2) | (3) |
|---|---|---|---|
| carrier concentration of layer B, D $N_{B,D}$ [$cm^{-3}$] | $6.9\times10^{15}$ | $6.9\times10^{15}$ | $8.7\times10^{15}$ |
| $n_B/n_{A,E}$ | 1.0005 | 1.005 | 1.08 |
| $N_A$ [$cm^{-3}$] | $6.3\times10^{18}$ | $7.9\times10^{17}$ | $5.5\times10^{17}$ |
| $N_E$ [$cm^{-3}$] | $8.7\times10^{17}$ | $1.1\times10^{17}$ | $7.6\times10^{16}$ |
| Al component $x_{A,E}$ | 0 | 0.03 | 0.48 |
| $n_B/n_C$ | 1.001 | 1.005 | 1.08 |
| $N_C$ [$cm^{-3}$] | $1.7\times10^{18}$ | $1.1\times10^{17}$ | $7.6\times10^{16}$ |
| Al component $x_C$ | 0 | 0.03 | 0.48 |
| width of layer B $a_1$ [μm] | 2.5 | 1.1 | 0.34 |
| width of layer C d [μm] | 1.8 | 2.4 | 0.93 |
| width of layer D $a_2$ [μm] | 4.3 | 1.2 | 0.36 |
| modulator length L [mm] | 2 | 2 | 1 |
| P/Δf for 10 % modulation [μW/MHz] | 18 | 6.3 | 3.3 |

Table II Design examples of strip-loaded GaAs modulator
[$\lambda_0$=1.06 μm, $E_{11}^x$ mode]

| | (1') | (2') |
|---|---|---|
| $N_A$ [$cm^{-3}$] | $2\times10^{18}$ | $2\times10^{18}$ |
| $N_B$ [$cm^{-3}$] | $5\times10^{15}$ | $1\times10^{15}$ |
| $N_C$ [$cm^{-3}$] | $2\times10^{18}$ | $5\times10^{18}$ |
| a [μm] | 5 | 6 |
| b [μm] | 3 | 2 |
| d [μm] | 3 | 3 |
| L [mm] | 2.9 | 3.3 |
| P/Δf for 20 % modulation [μW/MHz] | 1.7 | 0.85 |

Modulator length L is equal to the complete power exchange length.