Modulation characteristics of high-speed optical modulators with properly split asymmetry into their Mach-Zehnder arms

J. Nayyer, H. Nagata, S. Shimotsu, S. Oikawa and M. Yamada

Indexing term: Optical modulation

Successful fabrication of high-speed asymmetric lithium niobate modulators is reported. The frequency chirping and half-wave drive voltage can be adjusted via the extent of the asymmetry. The degradation of the extinction ratio is shown to be avoidable as the consequence of properly split asymmetry on to the Mach-Zehnder arms.

Introduction: External optical modulators were initially proposed to overcome the bandwidth limitation of optical communication systems caused by the frequency chirping associated with direct modulation of semiconductor lasers. The chirp phenomenon was investigated in several external modulators with the conclusion that interferometric Mach-Zehnder structures can exhibit chirpfree operation if the induced phase changes are equal but opposite in sign [1]. However, in high-speed modulations of the *z*-cut $LiNbO_3$ substrates, the travelling-wave information must propagate along planar structures with a ground electrode much wider than the hot one [2]. This results in unbalanced push-pull operation and realisation of residual frequency chirping becomes inevitable [3]. To overcome this difficulty, the authors introduced asymmetry into the Mach-Zehnder structure and investigated its influences on frequency chirping, half-wave drive voltage and thermal drift behaviour [4, 5]. It was shown that the thermal drift is improved and there is a tradeoff behaviour between the frequency chirping and the half-wave drive voltage (V_π). However, in practice, the extinction ratio drops off quite rapidly because of even a very slight loss difference between the asymmetric arms.

In this Letter, fabrication of asymmetric Mach-Zehnder $LiNbO_3$ optical modulators with modulation speeds in excess of 10GHz and improved chirp parameter and drive voltage are reported. High extinction ratios comparable to those of the conventionally symmetric Mach-Zehnder structures are achieved as the consequence of equalised losses comprised of taper and propagation losses (titanium-concentration-dependent) between the waveguide arms.

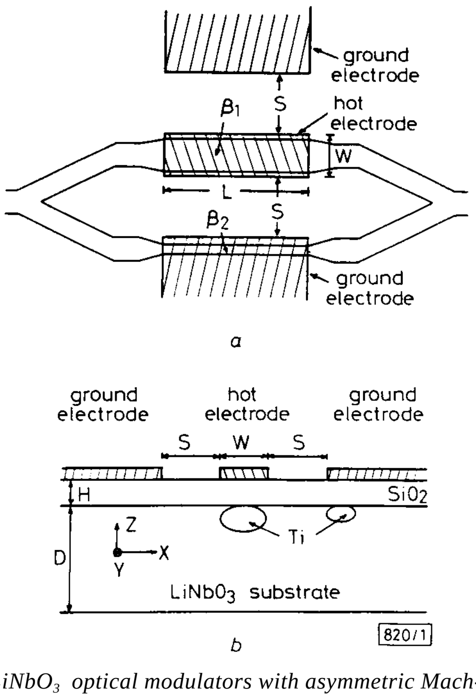

Fig. 1 *$LiNbO_3$ optical modulators with asymmetric Mach-Zehnder structures*

a Top view
b Cross-section

Design considerations and fabrication: Fig. 1 shows the top view and cross-section of the asymmetric optical waveguide arms. The optical waveguides are formed on top of the *z*-cut substrate by Ti diffusion at 980℃ for 20 h. The structural parameters of the fabricated modulators are summarised in Table 1. The asymmetry is introduced by adjustment of Ti widths before increasing the temperature. Because the propagation losses are slightly different in the parallel arms, the taper slopes must be adjusted to give equalised propagation losses.

Table 1: Structural parameters and measured modulation specifications of fabricated asymmetric moulators

Type / Parameter	A	B	C	D	E	F
Electrode width W, µm	7	7	7	7	7	7
Electrode spacing S, µm	15	15	15	15	15	15
Electrode length L, cm	4	4	4	4	4	4
Substrate thickness D, mm	0.5	0.5	0.5	0.5	0.5	0.5
Buffer-layer thickness H, µm	1	1	1	1.5	1.5	1.5
Ti width (hot), µm	7	7	5	7	7	5
Ti width (ground), µm	6	5	7	6	5	7
Half-wave voltage $V\pi$, V	3.44	3.44	3.84	4.32	4.64	5.04
Residual chirp ν	0.55	0.6	0.5	0.6	0.7	0.6
Bandwidth, GHz	9.49	9.64	8.87	11.39	10.94	11.03

Performance evaluation and discussion: The fabricated modulators were tested and their modulation parameters were measured. The results are summarised in the lower section of Table 1. As can be seen, high speed modulation is achieved in A, B and C modulators at low drive voltages smaller than 4V. In particular, the drive voltages of A and B modulators (7µm waveguide under the hot electrode) are smaller than those of C modulators (5µm waveguide under the hot electrode) by 0.4V. This is the consequence of stronger interaction (overlap integral) as reported previously [5]. On the other hand, the residual chirp parameter of a C modulator is better (than those of A and B), which is the consequence of a more balanced push-pull operation. This is, to our best knowledge, the lowest reported frequency chirping realised in a high-speed *z*-cut orientation. In D, E and F modulators for which the SiO_2 buffer layer is thicker, resulting in faster modulation, the drive voltage of an E modulator is smaller, while its chirp parameter is larger than that of an F modulator. These similar trends indicate that introduction of the asymmetry into Mach-Zehnder arms can be used to adjust the chirp parameter or the drive voltage.

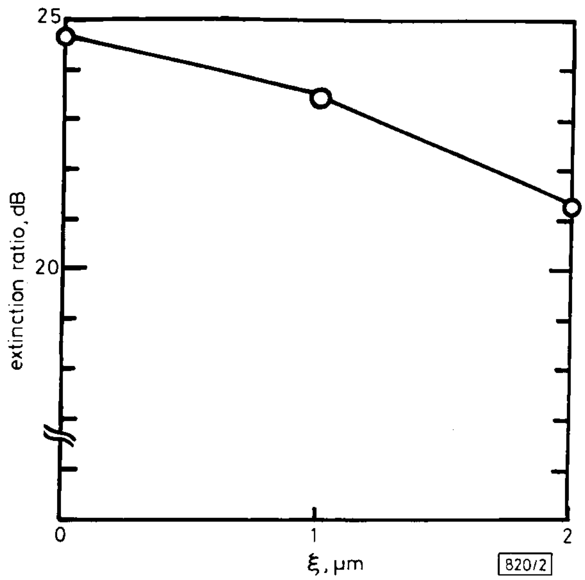

Fig. 2 *Extinction ratios of asymmetric modulators against extent of asymmetry ξ (i.e. waveguide size difference before diffusion process)*

Fig. 2 shows the extinction ratios of the asymmetric modulators again the extent of asymmetry ξ [µm], which is defind as the diffrence of the waveguide widths. As can be seen, in the conventionally symmetric modulator (i.e. $\xi = 0\mu m$), an extinction ratio of ~24dB can be achieved. As mentioned earlier, the extension ratio of the asymmetric Mach-Zehnder structures decreases as a consequence of loss difference between waveguide arms. However, degradation of the extinction ratio can be avoided at loss-equalised structures and a ratio of ~22dB can be achieved even at $\xi = 2\mu m$. In the trial asymmetric modulator with no attempt at loss equalisation, the extinction ratio degraded down to about 11 dB, which renders it useless in system applications.

As a final point, it should be mentioned that in Mach-Zehnder structures with the asymmetry discussed here, there is a reverse behaviour in regard to the drive voltage and the chirp parameter. If asymmetry is introduced in the arm length, there would be a similar tendency, as reported previously [6].

Conclusion: High-speed $LiNbO_3$ modulators with asymmetric Mach-Zehnder structures were fabricated. It was shown that the drive voltage and chirp parameter can be adjusted by the extent of asymmetry. Degradation of the extinction ratio was avoided by equalisation of the losses of the parallel arms.

Acknowledgments: J. Nayyer and H. Nagata are thankful to Y. Suematsu (ex-president of the Tokyo Institute of Technology). The authors thank their colleagues at Central Research Laboratories of Sumitomo Osaka Cement Co., Ltd.

3 January 1995
Electronics Letters Online No: 19950263

J. Nayyer, H. Nagata, S. Shimotsu, S. Oikawa and M. Yamada (*Central Research Laboratories, Sumimoto Osaka Cement Co., Ltd., 585 Toyotomi-cho, Funabashi-shi, Chiba 274, Japan*)

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