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Nanosecond response of bulk-optical Bragg-diffraction modulator based on periodically poled $LiNbO_3$

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Abstract

For the first time transients are measured for a bulk-optical Bragg-diffraction modulator based on an electro-optically induced grating in periodically poled $LiNbO_3$ (PPLN). Optical pulse risetimes of 1.2 nsec are reported with a first order diffraction efficiency of 76 % for circular Gaussian beams. The fast risetime is accounted for by a substantially suppressed excitation of acoustic thickness modes and careful electrode design. The device could replace acousto-optical Bragg-deflectors for many applications due to a reduction of the risetime by more than an order of magnitude.

Keywords

Electrooptic deflectors, electooptic switches, gratings, transient analysis, acoustic resonators.

I. INTRODUCTION

Currently available acousto-optical Bragg modulators are mainly limited by the relatively slow risetime of ~ 15 nsec. Shorter risetimes result in unacceptably low diffraction efficiencies [1]. For applications where higher switching speed and no frequency shift are required, such as Q-switching and deflectors used in the pre-press industry [2], electro-optical deflectors are preferable. In the past bulk-optical grating deflectors in single-domain $LiNbO_3$ using electro-optic modulation made launching of a highly elliptical beam through the crystal necessary in order to increase the diffraction efficiency [3], [4]. Such unwanted beam shaping methods are made obsolete by having a uniform index grating in depth which can be accomplished by domain inversion and applying a uniform electric field between the surface electrodes. Moreover, it has been suggested that domain-inversion shifts piezoelectric resonances to higher frequencies compared to single-domain $LiNbO_3$ modulators allowing faster optical pulses to be generated. This has been first demonstrated in a short device operating in the Raman-Nath regime by Blistanov *et al* [5] using electric field poling at elevated temperatures. With the advent of domain inversion via an applied electric field at room temperature [6] this technique has been employed to demonstrate Bragg switches [7], [8]. But so far, to the best of our knowledge, no transient measurements of the diffracted light for such a Bragg switch has been reported.

In this Letter we describe measurements on diffraction efficiencies for Bragg switches based on PPLN for both statically and dynamically applied electric fields. Furthermore, measurements on acoustic resonances for these grating modulators are presented and compared with those for unpoled samples. Various design parameters influencing the electro-optic and acousto-optic performance are discussed with respect to diffraction efficiency and switching time.

II. DESIGN AND FABRICATION

The Bragg switching device used for the measurements is depicted in Figure 1. It consists of an area of periodically domain-inverted regions forming a grating of length $L = 20$ mm and period $\Lambda = 40\ \mu$m with its planes orthogonal to the crystal's x-axis, Fig. 1(a). For the wavelength of $\lambda = 633$ nm the grating has a Q-value of 20 allowing a moderate divergence of the launched beam incident upon the grating at a Bragg angle Θ of 0.2^0. By applying a uniform electric field E_3 between the z-face electrodes a first order periodic refractive index change with an amplitude of $\Delta n = (2/\pi) \cdot n_e^3 \cdot r_{33} \cdot E_3$ is induced for z-polarized light with n_e and r_{33} as the respective refractive index and electro-optic coefficient. For maximum power transfer into the first diffracted order, where $\Delta n = \lambda/2L$, the theoretical field strength is $E_3 = 75$ V/mm for the values given. In order to facilitate fast switching the capacitance of the device has been reduced to ~ 5 pF by using a top strip electrode, which is orientated parallel to the launched beam. The width w of the strip electrode is equal to the wafer thickness d of 300 μm, Fig. 1(b). This configuration provides a quasi-uniform field in the region of the launched beam.

For the preparation of the switching devices we used z-cut $LiNbO_3$ wafers from Koto Electric Co., Ltd., Japan. The preparation itself can be subdivided into 3 major steps which are : I) etching of alignment marks, II) domain inversion, and III) deposition of the surface electrodes.

In order to provide an exact Bragg angle between the grating and the top strip electrode alignment aids were etched into the -z face through a photoresist pattern by using a reactive ion beam etcher. After thorough cleaning of the samples, photoresist grating patterns with different mark-to-space ratios were deposited on the -z face with respect to the alignment aids. For the poling process we used liquid electrodes [9]. The samples were poled by applying a time varying voltage so as to produce a carefully controlled current during the process. After reaching a pre-defined charge the high voltage was reduced. For the top electrode a 500 nm thick Chromium-Gold layer was thermally evaporated onto the -z face. A photoresist pattern was then deposited on top of the metal layer with respect to the alignment aids. In the next step the samples where chemically etched revealing the top strip electrode, followed by depositing the bottom planar electrode. The x-z plane endfaces were then polished to optical grade. Finally, the samples were annealed in air at $T = 300^{\circ}$ C for 5 h in order to allow the internal field to realign to the spontaneous polarization in the inverted regions [8], analogous to the observations made in $LiTaO_3$ [10].

III. RESULTS AND DISCUSSION

The optical measurements were performed with a frequency stabilized 633 nm HeNe laser linearly polarized parallel to the crystal's z-axis. The laser beam was transformed by spherical lenses to a circular beam with a confocal parameter $b \sim 48$ mm, thus keeping the grating well inside the region where the wavefronts are substantially plane. The sample was positioned with its center, $y = L/2$, at the location of the beam waist.

For the static measurement the 0th order refraction efficiency and the 1st order Bragg-diffraction efficiency were measured for different applied voltages U_{tb} between the top and bottom electrode, see Fig. 2. These functions agree qualitatively well with theory, as shown by the fitted sinusoids. We obtained 76 % and 6 % for maximum and minimum 1st order diffraction efficiency, respectively. The reduction of the efficiency contrast, with a maximum value of $\sim$ 88 % at $U_{tb} = 4$ V, may be explained by a slightly nonuniform grating, i.e. varying mark-to-space ratio. The offset voltage, necessary for minimum diffraction efficiency [7], [8], might be caused by the existence of an internal field, which was not fully realigned to the spontaneous polarization in the poled regions by the annealing process. The voltage for maximum power transfer between 0th and 1st order is $U_{tb} = 23.5$ V which is in very good agreement with the calculated required voltage of $U_3 = E_3 \cdot d = 22.5$ V.

For the dynamic measurements we used a pulse generator (model 2600C) from Picosecond Pulse Labs, USA. The transmission line from the pulse generator was terminated with 50 Ω in parallel, and in close proximity, to the sample. In order to provide a good contact between the sample electrodes and the connecting wires we used a small droplet of Gallium.

First we measured the efficiencies for 0th and 1st order using a 125 MHz DC coupled photodetector (model 1801) from New Focus, USA, by application of 100 nsec wide electric pulses of 25 V amplitude, Fig. 3(a). By comparison with Fig. 2 it is apparent that nearly the same 0th and 1st order efficiences have been achieved. The differences, we believe, are due to slight variations in the optical alignment for the two measurements.

In order to measure the transients more accurately we used a 1GHz AC coupled photodetector (model 1601) from New Focus. Figure 3(b) shows the optical pulse response of the diffracted first order for 100 nsec and 20 nsec wide pulses. Compared to Fig. 3(a) the electric pulse amplitude is unaltered. The measured optical pulse amplitude can therefore be directly related to the efficiencies, given in Fig. 3(a). The measurements in Fig. 3(b) show no resonant behaviour. The spike at around 120 nsec and its slow decay is accounted for by the pulse generator. Figure 3(c) shows the optical pulse response for a 5 nsec wide pulse with the optical pulse amplitude the same as in Fig. 3(b). Therefore we measure the same diffraction efficiency of 80 % for 5 nsec electric pulses as for the static excitation, Fig. 2. The 10 % to 90 % risetime $\tau_{r,m}$ of the signal in Fig. 3(c) is $\tau_{r,m} = 1.4$ nsec. Deconvolving the measured risetime and the instrumental risetimes we obtain an actual risetime of $\tau_r \sim 1.2$ nsec.

The performance of electro-optic devices is generally limited by the effect of electrode capacitance on risetime and by the excitation of acoustic modes via the piezoelectric effect [11]. The strength of excitation and persistence of these modes is determined by electromechanical coupling constants k and the acoustic Q associated with these modes, respectively. Fast edges and short pulse durations enable transient excitation of these modes over a wide frequency range. We therefore measured the frequency response of the piezoelectric feedback generated by these modes, again with a 50 Ω load parallel to the devices. Figure 4 shows the variation of the modulus of S_{11} with frequency for the device described above and for an unpoled but otherwise identical device. For the unpoled sample both thickness longitudinal mode resonances at $\sim$ 11.8 MHz and odd harmonics, and thickness shear mode resonances at $\sim$ 5.75 MHz and integer harmonics are clearly visible. The thickness shear modes are excited by the x-component of the fringing field in the neighbourhood of the top electrode edges, see Fig. 1. This results in a situation where resonances occur at all integer multiples instead of the more usual odd harmonics of the "textbook" parallel plate piezoelectric resonator. By comparing the frequency response for the poled sample with the one of the unpoled sample it is evident that the excitation of both types of thickness modes is approx. an order of magnitude smaller, which corresponds to a faster transient response. The observed substantial but not full suppression of these resonances, as in [5], might be attributed to the much smaller ratio d/Λ which is 7.5 and 125 in our case and in [5], respectively.

Regarding the design of this device a moderate ratio d/Λ should be chosen to (a) suppress the excitation of acoustic thickness modes, (b) maximise the diffraction efficiency, (c) minimise the driving voltage. A thin strip electrode substantially reduces the device capacitance. The drawback of the possible excitation of thickness shear modes is remedied by using PPLN.

IV. CONCLUSION

We have demonstrated a bulk-optical Bragg-diffraction modulator in PPLN with, in comparison to acousto-optical Bragg-deflectors, similar diffraction efficiency but more than 10 fold reduction in switching time, which is attributed to a substantial suppression of acoustic thickness modes and reduction of device capacitance.

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REFERENCES

[1] D. Maydan, "Acousto-optical pulse modulators," *IEEE J. Quantum Electron.*, vol. QE-6, pp. 15-24, 1970.

[2] British Patent Application; application number 9807738.1.

[3] M.A.R.P. de Barros and M.G.F. Wilson, "Nanosecond baseband optical-diffraction modulator," *Electron. Lett.*, vol. 7, pp. 267-268, 1971.

[4] J.M. Hammer, "Digital electro-optic grating deflector and modulator," *Appl. Phys. Lett.*, vol. 18, pp. 147-149, 1971.

[5] A.A. Blistanov, A.A. Danilov, D.A. Rodionov, N.G. Sorokin, Yu.G. Turkov, and S.I. Chizhikov, "Modulation and conversion of light in lithium niobate crystals with a regular domain structure," *Sov. J. Quantum Electron.*, vol. 16, pp. 1678-1679, 1986.

[6] M. Yamada, N. Nada, M. Saitoh, and K. Watanabe, "First-order quasi-phase matched LiNbO$_3$ waveguide periodically poled by applying an external field for efficient blue second-harmonic generation," *Appl. Phys. Lett.*, vol. 62, pp. 435-436, 1993.

[7] M.J. Brinkman, A. Romanovsky, X. Shao, S.J. Field, D.A.G. Deacon, and W.K. Bischel, "Electro-optic switches in poled lithium niobate," in *Digest of Conference on Laser and Electro-optics*, Washington , DC, 1996, paper CWD3.

[8] M. Yamada, M. Saitoh, and H. Ooki, "Electric-field induced cylindrical lens, switching and deflection devices composed of the inverted domains in LiNbO$_3$," *Appl. Phys. Lett.*, vol. 69, pp. 3659-3661, 1996.

[9] J. Webjörn, V. Pruneri, P.St.J. Russell, J.R.M. Barr, and D.C. Hanna, "Quasi-phase-mismatched blue light generation in bulk lithium niobate, electrically poled via periodic liquid electrodes," *Electron. Lett.*, vol. 30, pp. 894-895, 1994.

[10] V. Gopalan and M.C. Gupta, "Observation of internal field in LiTaO$_3$ single crystals: Its origin and time-temperature dependence," *Appl. Phys. Lett.*, vol. 68, pp. 888-890, 1996.

[11] P. Basséras, R.J.D. Miller, and S.M. Gracewski, "Theoretical analysis of acoustic transients in lithium niobate electro-optic modulators," *J. Appl. Phys.*, vol. 69, pp. 7774-7781, 1991.

[12] Y.F. Chen, S.N. Zhu, Y.Y. Zhu, N.B. Ming, B.B. Jin, and R.X. Wu, "High-frequency resonance in acoustic superlattice of periodically poled LiTaO$_3$," *Appl. Phys. Lett.*, vol. 70, pp. 592-594, 1997.

Fig. 1. Schematic of the grating deflector : (a) top view where x, y, z are the main axes of the one-domain $LiNbO_3$ crystal, L and Λ are the grating length and period, repectively, and Θ is the Bragg angle; (b) View at the $x - z$ plane in the domain inverted region where d is the wafer thickness and w is the top electrode width.

Fig. 2. 0th order refraction efficiency (o) and 1st order Bragg diffraction efficiency (•) versus the applied voltage U_{tb} between top and bottom electrode. The solid lines are fitted sinusoids.

Fig. 3. Time response of (a) the absolute 0th order (solid line) and 1st order (dotted line) optimum efficiency, and (b), (c) the relative 1st order diffraction efficiency by applying an electric pulse of (a), (b)(solid line) 100 nsec, (b)(dotted line) 20 nsec, and (c) 5 nsec duration.

Fig. 4. Magnitude of the S_{11}-parameter of an unpoled and poled $LiNbO_3$ sample, both with identical top strip electrode and bottom planar electrode, in the frequency interval 0 - 70 MHz.

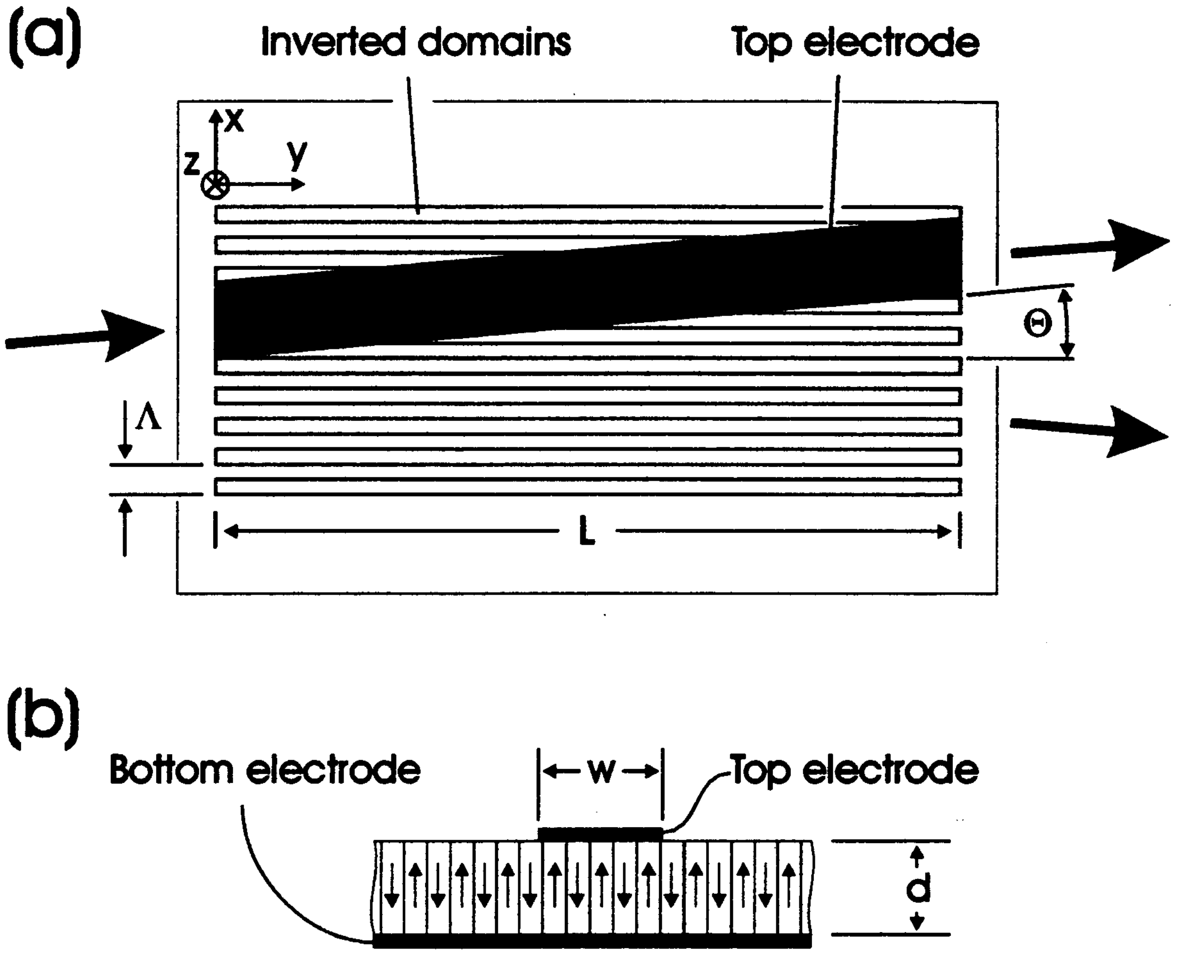
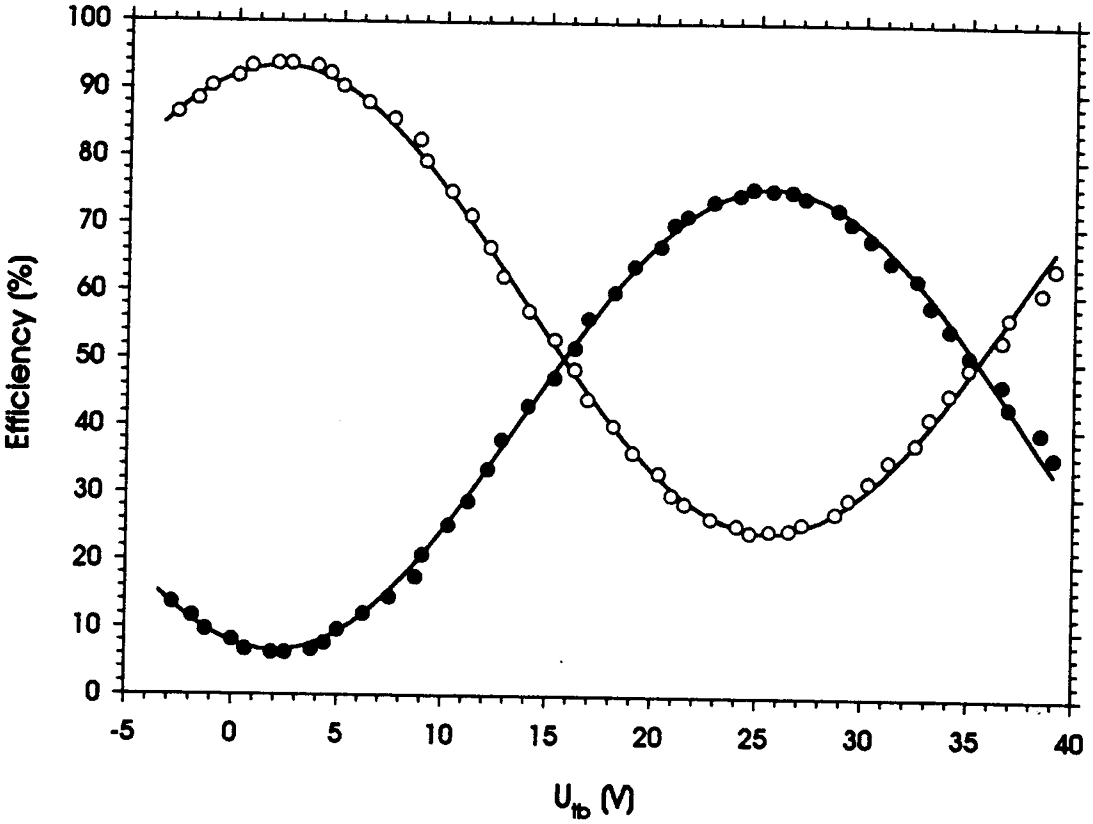


Fig. 1 : H. Gnewuch et al



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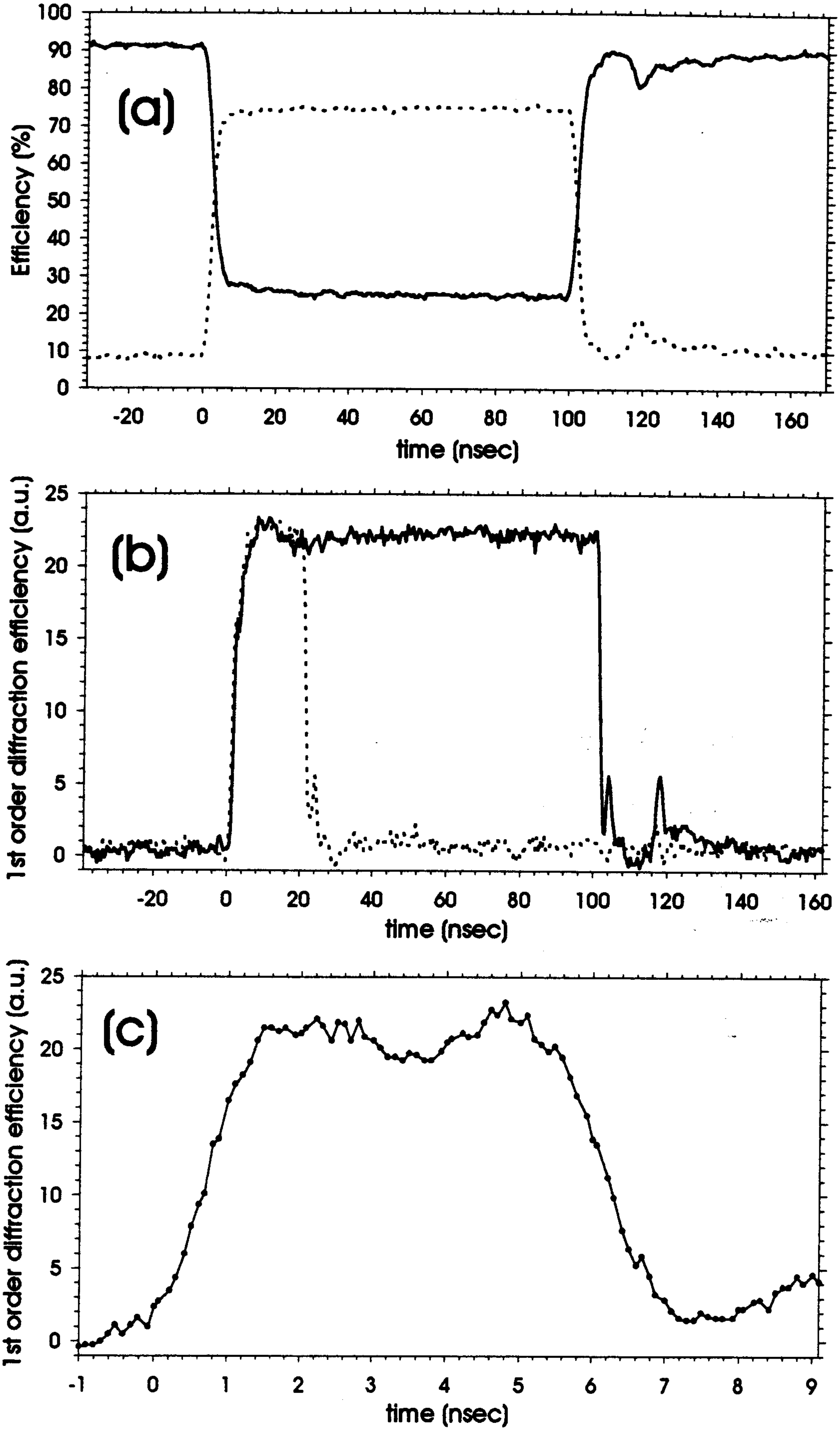

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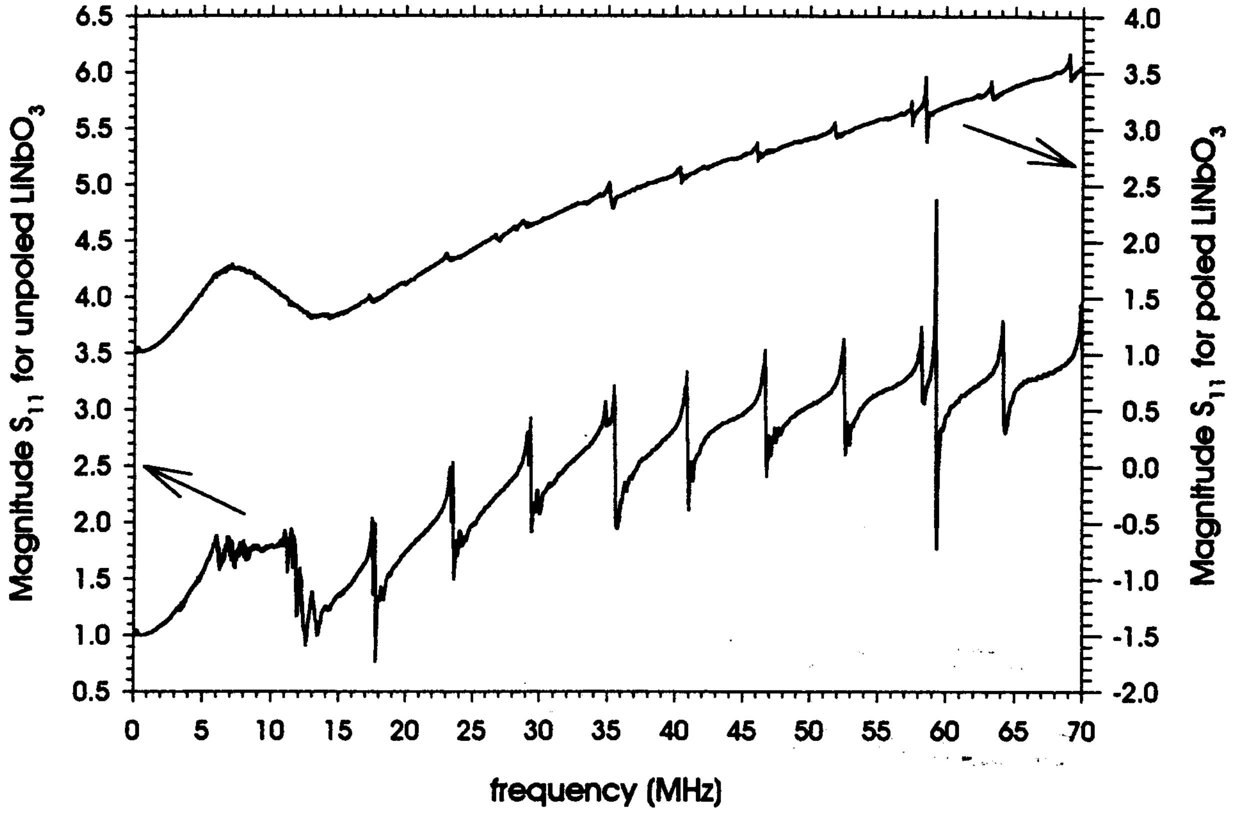

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