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Applications of guided waves to nonlinear optics

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Electromagnetic waves guided by single or multiple interfaces offer exciting possibilities for nonlinear optics because of the high power densities that can be achieved with small total powers. Progress in this area with the use of second-order and third-order nonlinearities is reviewed, including the current status of second harmonic generation by codirectional and contradirectional guided waves. A number of third-order nonlinear phenomena have recently been observed and are described. In particular, new nonlinear modes unique to guided waves have been verified to show optical limiter characteristics. Coherent anti-Stokes Raman scattering has been demonstrated experimentally in thin-film waveguides with unparalleled conversion efficiencies.

Introduction

Nonlinear interactions occur whenever the optical fields associated with one or more laser beams are large enough to produce polarization fields proportional to the product of two or more fields. These nonlinear polarization fields radiate with the generated field under optimum conditions (phase-matching), growing linearly with propagation distance; hence the key to obtaining efficient nonlinear optical interactions is to maintain high optical intensities over as long a distance as possible.

Optical beams can be confined to an optical wavelength in one dimension by total internal reflection at the boundary of a film whose refractive index is higher than its surroundings. Diffractionless propagation (in the confined dimension) occurs down the film for centimetre distances, limited by absorption or scattering or both. Nonlinear interactions can take place either in the film, or in the neighbouring media via the evanescent fields that accompany the guided wave. Rectangular channels with cross-sectional dimensions of optical wavelengths can also be used to confine optical beams optimally, provided that the channel region has a higher index than its surroundings.

Most nonlinear guided wave phenomena reported to date are analogues of similar interactions previously studied with plane waves. The nonlinear polarization is usually written as

$$P_{\mathrm{nl}} = \epsilon_0 \chi^{(2)} : EE + \epsilon_0 \chi^{(3)} \vdots EEE + \dots, \tag{1}$$

where $\chi^{(2)}$ and $\chi^{(3)}$ are the second-order and third-order susceptibilities respectively, and E is the total field. For second-order interactions, waves at the sum and difference frequencies of the input waves can be generated. In the third-order case for frequency inputs at ω_{a}, ω_{b} and ω_{c}, the nonlinear polarization and hence the radiated fields can have frequency components $\omega_{\mathrm{a}} \pm \omega_{\mathrm{b}} \pm \omega_{\mathrm{c}}$, which leads to a large range of phenomena. We discuss these various applications based on guided waves in this paper.

Second-order nonlinear phenomena

The principal application of second-order guided-wave nonlinearities is to the generation of second-harmonic radiation. For efficient conversion of codirectional waves, the effective refractive index of both the fundamental and harmonic waves must be equal (phase-matching), just as in the plane-wave case. Since a waveguide is inherently a dispersive medium owing to geometry alone, and because multiple solutions to the dispersion relations exist at a fixed frequency, waveguide phase-matching constraints are considerably less restrictive than those for plane waves.

The best results so far (Sohler & Suche 1983) have been obtained in channel in-diffused $LiNbO_3$ waveguides. Sohler & Suche (1983) have obtained a conversion efficiency of 10^{-3} with a 1 mW He–Ne laser. By making a matched resonator out of the channel waveguide those authors predict that this value can be increased by an additional order of magnitude. Further increases in efficiency will probably require the use of organic thin films (Stegeman & Liao 1983).

Generation of non-phase-matched second harmonics normal to the waveguide surface can be obtained by mixing two oppositely propagating guided waves (Normandin & Stegeman 1982), for example in Ti:in-diffused $LiNbO_3$ waveguides. As illustrated schematically in figure 1, this process can be used to take the autoconvolution of optical pulses in the picosecond

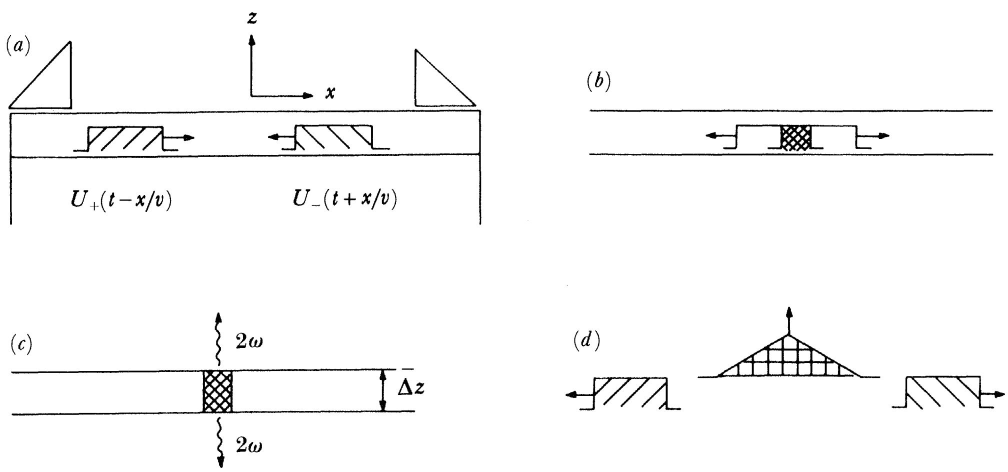

Figure 1. Schematic of the nonlinear mixing of two input waveforms that produce a convolution signal at the harmonic frequency: (*a*) two approaching pulse forms in a waveguide; (*b*) overlap of the two waveforms at an instant in time; (*c*) radiation by the polarization field; (*d*) convolution waveform generated by the nonlinear mixing of the (now departing) input pulses.

time domain. The harmonic convolution signal then falls on a charge carrier (c.c.d.) (which is a linear array of detectors) placed parallel to the surface. Hence the temporal autoconvolution of the waveform now appears as a spatially distributed, digitized signal along the c.c.d. array. This device has applications as a picosecond transient digitizer for capturing single events, provided that new highly nonlinear organic materials can be used (Liao *et al.* 1983).

Third-order nonlinear phenomena

The latest advances in the application of guided waves to nonlinear optics utilize third-order nonlinearities. Most of the reported experiments involve a field-dependent refractive index (or, equivalently, dielectric constant). In addition coherent anti-Stokes Raman scattering has been observed in waveguides.

Nonlinear guided waves

Many of the applications of third-order nonlinearities stem from a field-dependent refractive index. Rewriting (1),

$$P = P_1 + P_{\text{nl}} = \epsilon_0[n_0^2 + \chi^{(3)} \vdots EE]\, E, \tag{2}$$

where clearly the second term in the square brackets can be interpreted as a field-dependent refractive index. For plane waves the nonlinear term reduces to $2n_0 n_{2,E}|E|^2$ where $n_{2,E}$ is called the intensity-dependent refractive index. The situation for guided waves is more complex (Stegeman 1982). For isotropic waveguide media

$$P_{\text{nl},\,i} = 2n_0 n_{2,E}[\tfrac{2}{3}E_i E_j E_j^* + \tfrac{1}{3}E_i^* E_j E_j], \tag{3}$$

which differs from the plane-wave case when evanescent fields are involved, as is always true for guided waves.

Analytical dispersion relations can be obtained for nonlinear thin-film waveguides (Akhmediev 1982; Boardman & Egan 1984; Stegemen *et al.* 1984*a*). For TE-polarized waves (E parallel to the surface), one solves the nonlinear wave equation $\nabla^2 E - k_0^2[n_0^2 + \alpha|E|^2]\,E = 0$ in all of the waveguiding media and matches tangential boundary conditions across the film interfaces. For example for a film of thickness h and refractive index n_{f} bounded on one side by a linear medium of refractive index n_{s} and on the other by a nonlinear medium characterized by $n = n_0 + \alpha|E|^2$, the dispersion relation is

$$\tan(\kappa k_0 h) = \kappa[s \tan(s\kappa z_1) + p]/[\kappa^2 - sp \tan(sk_0 z_1)],$$

where $k_0 = \omega/c$, $\kappa^2 = n_{\text{f}}^2 - \beta^2$, $p^2 = \beta^2 - n_{\text{s}}^2$, β is the effective mode index and z_1 is related to the guided wave power. A numerical example is shown in figure 2, where curves a and b

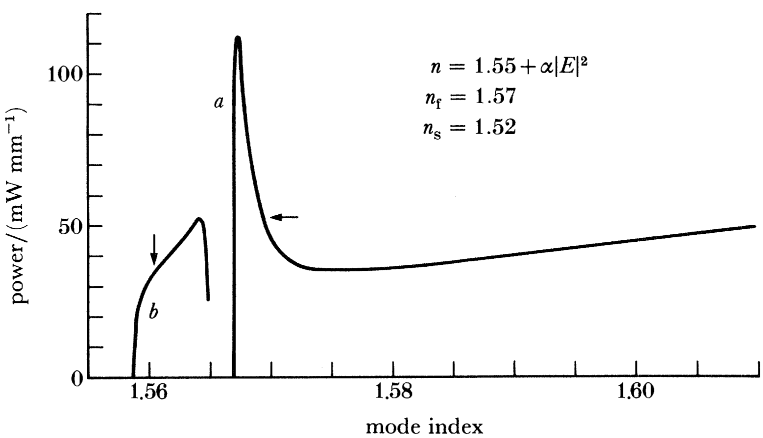

FIGURE 2. The mode index, β, versus the guided wave power for $TE_0(a)$ and $TE_1(b)$ modes guided by a film of thickness 2 μm.

correspond to the TE_0 and TE_1 modes. Note the maximum in the power that can be transmitted in both cases and that $\beta > n_f$ is possible. If both bounding media are nonlinear, or if the film is, multiple new modes are also predicted.

There is experimental evidence (Vach *et al.* 1984) for such power-dependent modes. Shown in figure 3 is the transmitted against incident TE_1 power for a glass waveguide with a liquid-crystal medium on top. The limiting action is clearly shown, as well as the two modal branches that coexist at the same input power.

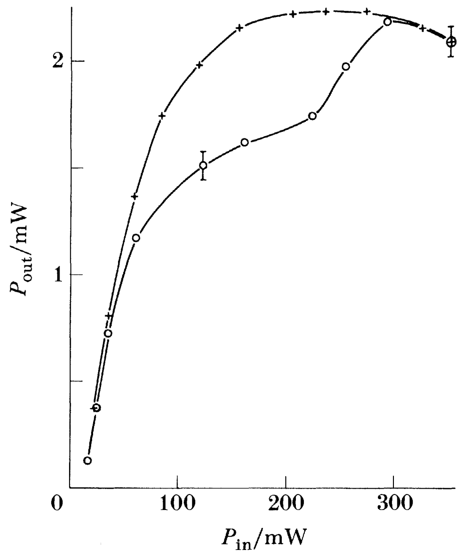

FIGURE 3. The power transmitted in the TE_1 mode for both increasing (+) and decreasing (○) incident powers.

Optical bistability

One of the important potential applications of a field-dependent refractive index is to optical bistability (Miller *et al.* 1979). The feedback required can be obtained by using gratings, either as mirrors or for distributed feedback (Winful *et al.* 1979; Winful 1981). Assuming a $\frac{1}{2}\pi$ phase shift is required (which is the maximum) and a highly nonlinear material such as InSb ($\lambda \approx 5.5$ μm) in thin film form, the power required for bistability can be as low as 15 μW mm^{-1} (Stegeman 1982) or even 10 nW in channel waveguides (Stegeman *et al.* 1984*b*). A collaborative programme is currently under way to test these concepts, involving researchers at the University of Arizona and Heriot-Watt University.

Nonlinear gratings can be used for a variety of all-optical functions. The Bragg condition at which maximum reflection occurs from a grating is $\boldsymbol{\beta}_s = \boldsymbol{\beta}_i + \boldsymbol{\kappa}$, where $\boldsymbol{\beta}_i$ and $\boldsymbol{\beta}_s$ are the incident and scattered guided wavevectors, and $\boldsymbol{\kappa}$ is the grating wavevector. Since the β can be controlled optically, the grating characteristics can be controlled optically. This makes switching, logic, etc., all possible.

Nonlinear couplers

The operation of distributed couplers such as prisms and gratings is changed for nonlinear waveguides. This has been pointed out by Carter & Chen (1983), who predicted switching, and by Liao & Stegeman (1984), who showed that the coupling efficiency can be dramatically reduced. In a prism of refractive index n_p, for example, optimum coupling is usually obtained when light is incident through the prism at an angle θ to the surface normal such that $\beta = n_p k_0 \sin\theta$. If β depends on guided wave power, this synchronous coupling condition is lost and coupling efficiency falls.

Coherent couplers

A coherent coupler consists of two almost identical parallel channel waveguides in close enough proximity for the guided wave fields of one to overlap the other. Light introduced into one channel is transferred to the second after a characteristic distance, which varies inversely with $\Delta\beta$, the difference in propagation constants of the two waveguides (Jensen 1982). For an intensity-dependent wavevector the coupling condition becomes power-dependent. This effect has been observed with $LiNbO_3$ channel waveguides (Lattes *et al.* 1984) and is discussed by Hans & Whitaker (this symposium).

Coherent anti-Stokes Raman scattering

Coherent anti-Stokes Raman scattering is the nonlinear mixing of two photons at frequency ω_1 with one photon at frequency ω_2 to produce a nonlinear polarization field at frequency $2\omega_1-\omega_2$. The key is to arrange the propagation wavevectors so that $2\boldsymbol{\beta}_1-\boldsymbol{\beta}_2=\boldsymbol{\beta}_3$, where $\boldsymbol{\beta}_3$ is a guided-wave wavevector of frequency $2\omega_1-\omega_2$, i.e. the process is phase-matched. Under these conditions, the signal power, P_3, is (Stegeman *et al.* 1983)

$$P_3 \propto L^2 \left| \chi_b^{(3)} + \sum_r \frac{\chi_r^{(3)}}{(\omega_1-\omega_2-\omega_r)+\mathrm{i}\Gamma_r} \right|^2 P_1^2 P_2, \tag{4}$$

where L is the propagation distance, and $\chi_b^{(3)}$ and $\chi_r^{(3)}$ are the background and resonance terms respectively. As the difference frequency, $\omega_1-\omega_2$, is tuned through a Raman transition (frequency ω_r and lifetime Γ_r^{-1}), the signal is resonantly enhanced and both the frequency, ω_r, and linewidth, Γ_r, can be determined.

This phenomenon has been observed in thin-film polystyrene waveguides (Hetherington *et al.* 1984). For the characteristic 992 cm^{-1} vibration of a ring structure, a peak signal corresponding to 0.2% conversion of the incident into the spectroscopic signal has been measured, demonstrating the very high efficiency of this technique.

Summary

Nonlinear integrated optics is, with the exception of second-harmonic generation, a young emerging technology. Guided waves are the optimum means of providing the high power densities and long interaction distances necessary for practical applications of nonlinear optics. Within the last year, nonlinear guided waves, nonlinear coherent couplers, intensity-dependent coupling and coherent anti-Stokes Raman scattering have all been observed. One can confidently expect that both degenerate four-wave mixing and bistability will both be reported before the end of 1984.

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