Optica Applicata, Vol. XXIV, No. 4, 1994

Optically induced gratings in waveguides and waveguide couplers

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The coupling of non-phase matched modes in waveguides and waveguide couplers by means of a diffraction grating formed by two external control beams interfering in nonlinear material is analyzed. The parameters of the grating depend on the control fields properties and the external power controlled coupling of a chosen pair of modes can be realized.

1. Introduction

The gratings formed by periodic changes of dielectric constant distribution are used in integrated optics for a variety of purposes including the construction of filters, input couplers and Bragg reflectors. If the grating constant $K = 2\pi/\Lambda$ (where Λ is the grating period length) is matched to the propagation constants difference of two modes, the efficient coupling between different modes or different waveguides can be obtained.

The gratings in integrated optics elements are usually formed during the fabrication processes and have constant, immutable parameters, which limits the operation of the device to one, strictly defined frequency. In this paper, we consider a nonlinear waveguides array with the optically induced grating. The grating is formed by spatially periodic changes of the refractive index which results from the interference of two external fields in a nonlinear medium. Parameters of the grating depend on the external waves and can be varied during the work of the device.

2. Coupling equations

The grating is created by two beams at frequency ω_{ex} propagating in different directions and overlapping in the nonlinear medium. These fields are approximated here by plane waves with slowly varying amplitudes $A_{ex}(x,y,z,t)$ of the same transverse distribution. Reflections of the waves at the waveguide boundaries are neglected to simplify the calculations. The intensities are assumed to be much higher than intensities of guided modes. Hence the total electric field in nonlinear interaction region can be approximated by a sum of external waves fields only. Propagation directions of the control waves are chosen to obtain an interference pattern along the way of the guided modes (zaxis). The nonlinear change of the dielectric constant is $\Delta\varepsilon^{NL} = 2\alpha^{NL}|A_{ex}|^2[1+\cos(Kz)]$, where α^{NL} describes nonliner properties of the system. The grating constant K depends on the frequency and the incidence angles of the external waves, $K = 2\beta_{ex}$, where β_{ex} is the value of z-component of their wave vectors. The intensities of all interacting waves are assumed to be relatively low, so that the nonlinearity allows generatinon of small index changes in the nonlinear medium but does not change the properties of the modes.

The scattering of light on the periodic structure can be analyzed as a coupled-mode process. General equations describing the coupling of an arbitrary pair of codirectional or contradirectional modes of an array of N parallel waveguides with the optically induced grating were derived in work [1]. Coupled mode equations for one pair of codirectional modes are:

$$i\frac{dA_\mu}{dz} = G^{(+)}_{\mu\nu}A_\nu(z)\exp[i(\beta_\mu-\beta_\nu)z]\exp(-iKz),$$
$$i\frac{dA_\nu}{dz} = G^{(+)}_{\nu\mu}A_\mu(z)\exp[-i(\beta_\mu-\beta_\nu)z]\exp(iKz) \tag{1}$$

and for contradirectional ones are:

$$i\frac{dA_\mu}{dz} = G^{(-)}_{\mu\nu}B_\nu(z)\exp[-i(\beta_\mu-\beta_\nu)z]\exp(-iKz),$$
$$-i\frac{dA_\nu}{dz} = G^{(-)}_{\nu\mu}A_\mu(z)\exp[-i(\beta_\mu-\beta_\nu)z]\exp(iKz). \tag{2}$$

The forward and backward fields envelops $A_\mu(z,t)$ and $B_\mu(z,t)$ are supposed to be slowly varying functions, β_μ are propagating constants. Coupling coefficients, $G^{(+)}$ and $G^{(-)}$, are defined by the following integrals:

$$G^{(+)}_{\mu\eta} = \omega\varepsilon_0\iint\Delta\varepsilon_G[\boldsymbol{E}_{t\mu}\times\boldsymbol{E}^*_{t\nu}+\varepsilon^{(\nu)}_L\varepsilon^{-1}\boldsymbol{E}_{z\mu}\times\boldsymbol{E}^*_{z\nu}]dzdy,$$
$$G^{(-)}_{\mu\eta} = \omega\varepsilon_0\iint\Delta\varepsilon_G[\boldsymbol{E}_{t\mu}\times\boldsymbol{E}^*_{t\nu}+\varepsilon^{(\nu)}_L\varepsilon^{-1}\boldsymbol{E}_{z\mu}\times\boldsymbol{E}^*_{z\nu}]dzdy \tag{3}$$

where: $\Delta\varepsilon_G = \alpha^{NL}|A_{ex}|^2$, $\boldsymbol{E}_{t\nu}$ and $\boldsymbol{E}_{z\nu}$ are transverse and longitudinal components of the guided waves electric field vectors. The grating constant K and grating amplitude $\Delta\varepsilon_G$ are variable here and the same device can couple codirectional or contradirectional modes depending on the actual value of K. The efficiency of the coupling depends on the external waves intensities.

3. Numerical example

The numerical calculations were performed for the short wavelength grating (Eqs. (2)) induced in a single planar waveguide. The fact that the way of the external waves through the nonlinear medium is very short (the thickness of the waveguide is in the range of micrometers) makes it possible to exploit materials with resonant nonlinearity, the use of which is normally limited by extremely strong absorption. The system is composed of about 1 μm thick GaAs/AlGaAs multiple-quantum-well (MQW) waveguide consisting of 6.5 nm thick GaAs quantum wells with 21.2 nm thick $Al_xGa_{1-x}As$ ($x = 0.4$) barriers and surrounded by two linear media ($\varepsilon_s = 10$). The refractive index of MQW structure depends on the density of optically generated electron-hole pairs [2], $\Delta n = n_{eh}(\omega_g)N(x,z)$, where $N(x,z)$ is the density of carriers, $N(x,z) \approx (\alpha_{ex}/\hbar\omega_{ex})I_a\Delta t$, for $I_a(x,z) = I_0[1/2+1/2\cos(Kz)]\exp(-\alpha_{ex}x)$ being the spatial distribution of the average pulse intensity resulting from the interference of the external waves. The absorption coefficient of MQW layer, for the fields of nearly resonant frequency [3] is $\alpha_{ex} \sim 1.2\times 10^4\,\mathrm{cm}^{-1}$. The guided modes wavelength, $\lambda_g = 1.55$ μm, was chosen in the range of the high transparency of the structure so that $\alpha_g \ll \alpha_{ex}$.

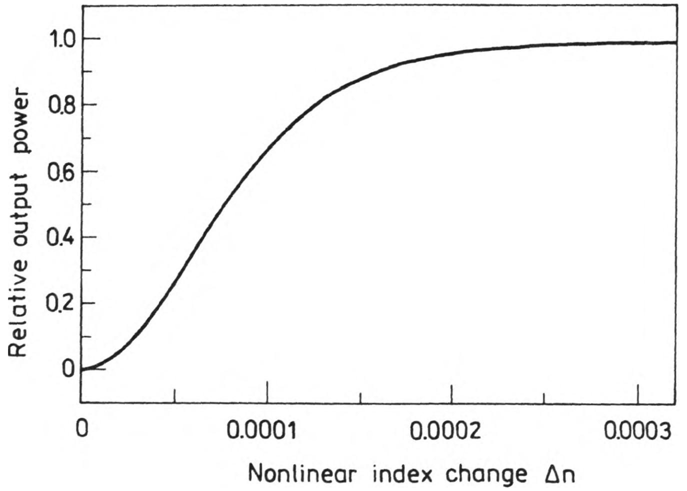

Fig. 1. Relative output power of TE^0 backward propagating mode as a function of the grating amplitude for 10 mm long grating with grating constant $K = 2\beta_\mu$

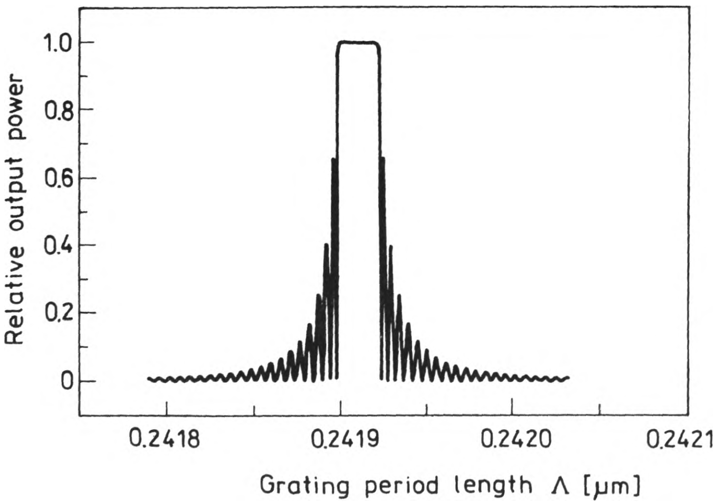

Fig. 2. Relative output power of TE^0 backward mode as a function of the grating period length for 10 mm long grating with amplitude $\Delta n = 3\times 10^{-4}$

We considered the reflection of TE^0 input mode from 10 mm long grating. The relative output power of the backward propagating mode, $P_\mu = |B_\mu(0)|^2/|A_\mu(0)|^2$, depending on the grating amplitude is presented in Fig. 1. The calculations were performed for the grating constant exactly tuned to the propagation constants differences $K = 2\beta_\mu$. The refractive index change for the waves of $\lambda_g \sim 1.55$ μm is due mainly to the polarizability of free carriers [4], [5]. The quantum efficiency n_{eh} is about 10^{20} cm^{-3} in that case and refractive index change $\Delta n \sim 3\times10^{-4}$, necessary to obtain switching requires the external waves pulses of $I_0\Delta t \sim 5\times10^{-7}$ J/cm^2.

The dependence of the relative output power on the grating period for the grating amplitude $\Delta n = 3\times10^{-4}$ is presented in Fig. 2. The grating period necessary for contradictional modes coupling is very short (about 0.24 μm) and the diffusion of carriers plays an important role. The recovery time of the grating τ has recombination τ_R and diffusion τ_D, contributions $1/\tau = 1/\tau_R + 1/\tau_D$ with $\tau_D = \Lambda^2/4\pi D_a$, where Λ is the grating period length. The recombination time and the diffusion coefficient for motion along the wells obtained by MILLER *et al.* [2] are $\tau_R = 86$ ns and $D_a = 16.2\times\mathrm{cm^2 s^{-1}}$, what gives the recovery time of about 10^{-12} s. The generation of such grating requires subpicosecond external waves pulses with the pulse separation much longer than the carrier recombination time. The dependence of sidelobes appearing in the output power on grating constant can be reduced using the external beams with smaller diameters [1].

4. Conclusions

It has been shown that an optically induced grating provides coupling between two guided modes in a nonlinear waveguides array. The efficiency of coupling can be varied during the work of the device. The grating constant can be tuned to the arbitrary frequency and type of modes. The practical realization of the device requires material with large nonlinearity which can be found with the resonant nonlinear mechanisms.

References

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