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Analysis of properties of the thin film structures $KNdP_4O_{12}/KLaP_4O_{12}$ with triangular and rectangular grating resonator*

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The neodymium stoichiometric compounds are interesting materials for thin film lasers. In such structures it is possible to obtain light generation at $\lambda = 1.06$ μm and $\lambda = 1.3$ μm (which are useful for optical communication). Because of high concentration of neodymium ions in that kind of compounds the absorption coefficient of pumping light and the gain coefficient for generated radiation are high too.

In this paper the threshold conditions for $KNdP_4O_{12}$ on $KLaP_4O_{12}$ thin film structure with distributed feedback (DFB) and distributed Bragg reflector (DBR) are formulated. The selectivity properties of that structure are also presented. The calculations are carried out for rectangular and triangular gratings. The coupling coefficient as a function of the structure parameters is discussed. The value of the coupling coefficient for rectangular grating is greater than that for the triangular one (for the same structure parameters) and the rectangular grating structures have a lower threshold gain.

For our analysis the following structure is considered. The thin layer of potassium neodymium tetraphosphate (KNP) is deposited on potassium lantanium tetraphosphate (KLP) — Fig. 1. Both the media are biaxial and one of principal axes in each medium is oriented in direction of propagation (z-axis). The other two principal axes, x and y, are perpendicular and parallel to the thin film plane, respectively.

The main purpose of our work is to determine the influence of structure parameters (such as: the grating period Λ, the grating depth c, the effective layer thicknes $\bar{t}$ or the grating shape) on the threshold gain and the frequency selectivity in the structures shown in Fig. 1.

Our calculations are carried out for TE modes and the wavelength equal to 1.06 μm. We use the value of the substrate refractive index equal to 1.58 and the refractive index of the guiding film (thin film of KNP) equal to 1.6.

The threshold condition for DFB structure (Fig. 1a) is described by

$$K = \pm j\gamma sh^{-1}(\gamma L) \tag{1}$$

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where: K — coupling coefficient (it is a measure of the strength of coupling between travelling waves going from left ($-z$ direction) and right ($+z$ direction)); L — length of the periodic structure; γ — complex propagation constant which

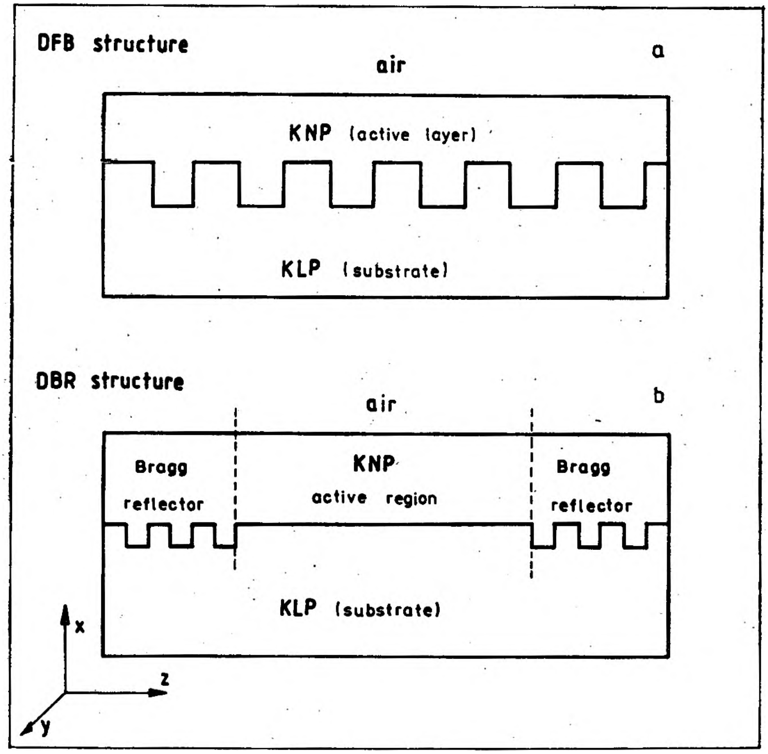

Fig. 1. Distributed feedback structure (DFB) — a, structure with distributed Bragg reflector (DBR) — b

obeys the dispersion relation $\gamma^2 = K^2+(g+j\delta)^2$ (g — gain coefficient, δ — measure of the departure of the oscillation frequency ω from the Bragg frequency ω_B, $\delta = n_{\mathrm{eff}}(\omega-\omega_B)/c$, n_{eff} — effective refractive index of the guiding film, $\omega_B = \pi c/\Lambda$, Λ — period of the grating, c — light velocity in the vacuum).

This threshold condition is obtained with the help of the well known coupled-wave theory developed by Kogelnik and Shank [1]. This relation can be solved numerically. The values of threshold gain and frequencies of oscillations for the first three longitudinal modes are shown in Fig. 2 as a function of the coupling coefficient K. As we can see, the threshold gain g decreases monotonically with the increasing K, but the frequency selectivity of the structure is worse for higher value of the coupling coefficient K.

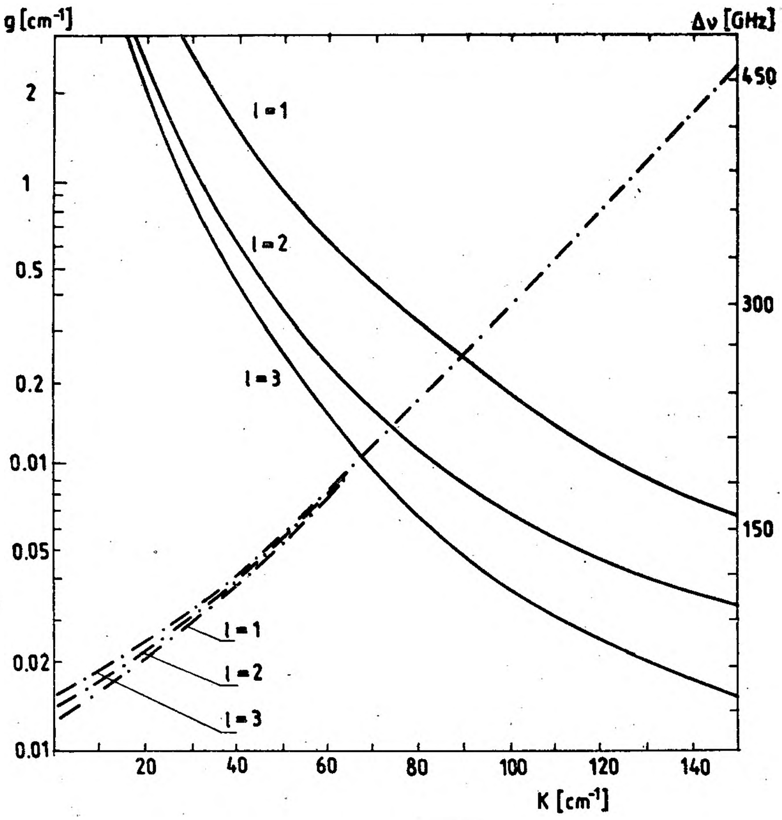

Fig. 2. Gain g required for threshold vs. coupling coefficient K (thick curve) and the frequency selectivity $\Delta\nu$ vs. K (dashed curve), l – mode number

According to the Wang theory [2] the threshold condition for DBR is described by

$$g = \frac{\varepsilon}{f(N_{\text{eff}})} + \frac{\ln\left(\frac{\alpha_R}{K}+1\right)}{Lf(N_{\text{eff}})} \tag{2}$$

where: g – gain coefficient in the active medium,
α_R – losses coefficient in the Bragg reflector region,
K – coupling coefficient,
L – length of active region,
ε – scattering losses [3],
$f(N_{\text{eff}})$ – function of normalized effective gain of guided modes [3].

The result of threshold condition calculation for DBR structure is shown in Fig. 3. For a greater gain coefficient, greater losses coefficient in the Bragg reflector region are admissible. The frequency selectivity of DBR structure is presented in Fig. 4, where reflectivity of Bragg reflector region is shown as a function of detuning δ from Bragg frequency [2].

As we can see, in the DFB and DBR laser devices the performance depends critically on the coupling coefficient K. This coefficient is usually defined in terms of the effect of the periodic variation in refractive index or gain coefficient along the length of the device, whereas in most DFB and DBR lasers the light

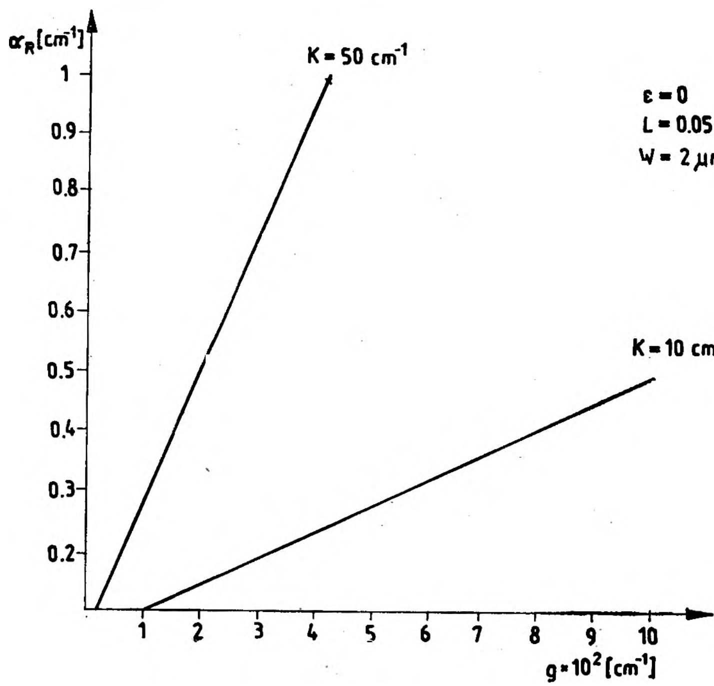

Fig. 3. Losses coefficient in the Bragg reflector region vs. gain coefficient of active region

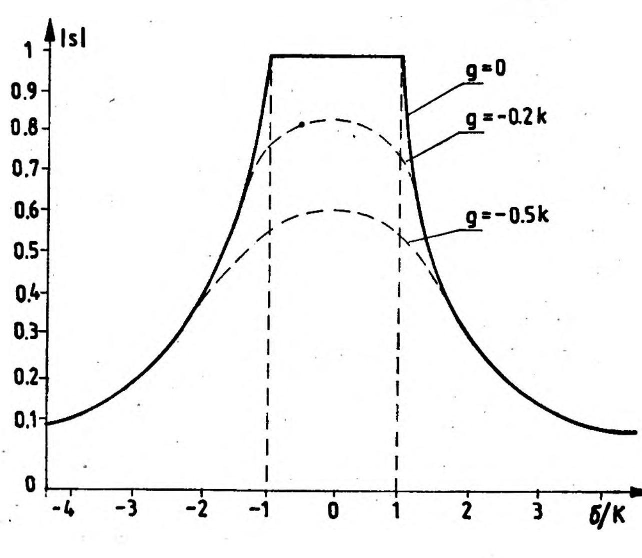

Fig. 4. Bragg reflector region reflectivity S vs. normalized detuning δ/K

is in fact perturbed by a periodic corrugation of the waveguided boundary.

Thus, when the threshold conditions for both structures are to be applied to real laser structures which employ corrugation, the coupling coefficient K must be related to the grating parameters. It has been done for rectangular and triangular gratings. The calculations were carried out using coupled wave theory and perturbation technique.

For rectangular grating the expression relating K to the grating parameters has the following form:

$$K_{dm} = \frac{\omega^2 \mu_0 \varepsilon_0 (n_f^2 - n_s^2)}{4\pi \beta_m N_m^2 d} \sin \frac{d\pi W}{\Lambda} \left\{ c_2 + \frac{\sin(2c_2 p)}{2p} + \frac{q}{p^2} \right.$$

$$\left. [1-\cos(2c_2p)] + \frac{q^2}{p^2}\left[c_2 + \frac{\sin(2c_2p)}{2p}\right] + \frac{1}{q}\,[1-\exp(-2c_1q)] \right\},$$

$$N_m^2 = \frac{(p^2+q^2)(\bar{t}+q^{-1}+h^{-1})}{2p^2},$$

$$h = \sqrt{\beta_m^2 - n_c^2 k_0^2},$$

$$p = \sqrt{n_f^2 k_0^2 - \beta_m^2},$$

$$q = \sqrt{\beta_m^2 - n_s^2 k_0^2},$$

$$k_0 = 2\pi/\lambda_0$$

where: p, q, h – propagation constants in propagation directions in substrate, film and coat, respectively,

n_f, n_s, n_c – refractive indices of the thin film, substrate and coat, respectively,

d – integer denoting the Bragg scattering order,

m – waveguide mode order,

λ_0 – wavelength in vacuum.

Other parameters are shown in Fig. 5.

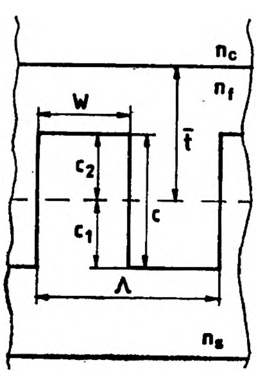

Fig. 5. Rectangular grating

The variation of absolute value of the coupling coefficient K with grating depth c for the first four TE modes is shown in Fig. 6. For all the modes the coupling coefficient K increases monotonically with the grating depth c, and for the given effective thickness, K is higher for higher mode number.

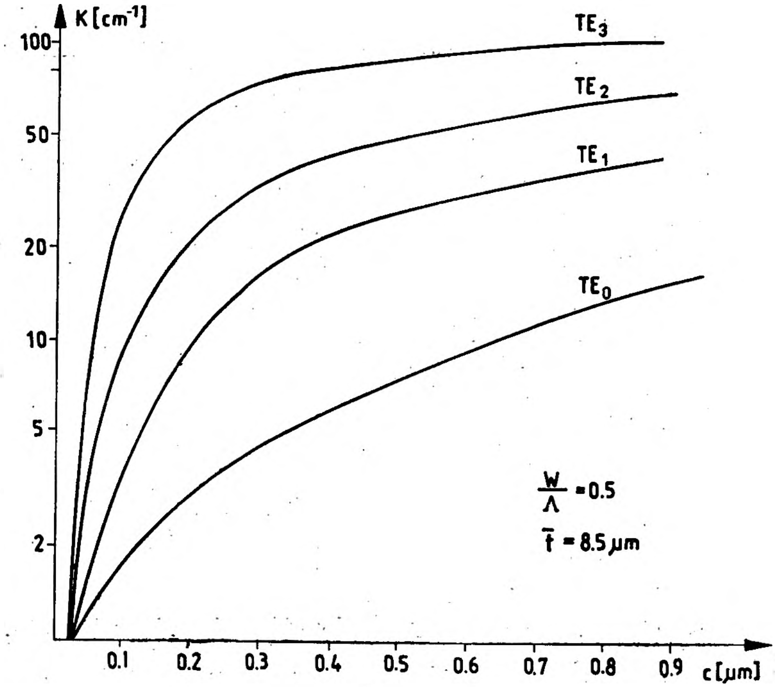

Fig. 6. Coupling coefficient K as a function of grating depth c for first four waveguide modes

In the next figure (Fig. 7) the absolute value of the coupling coefficient K vs. ratio W/Λ is plotted for TE_0 mode and different Bragg scattering orders. In general, the coupling coefficient K has a maximum value for certain W/Λ values which depends upon the Bragg order scattering.

In addition, as the ratio W/Λ changes there appear different degrees of interference from various parts of the tooth of the grating along the direction of the propagation which account for the zeros in the coupling coefficient K.

In Figure 8 we show the variation of the coupling coefficient K with the waveguide effective thickness $\bar{t}$. It can be noticed that each mode has its maximum value of K for certain $\bar{t}$ and that the maximum value of K decreases with the mode number.

For the triangular grating the expression relating K to geometrical parameters of structure is the following:

$$K_{m,d} = \frac{\omega^2 \mu_0 \varepsilon_0 (n_f^2 - n_s^2)}{4\pi \beta_m N_m^2 d} c \left\{ \left(1 + \frac{q^2}{p^2}\right) \frac{1 - \cos\left(\frac{\pi d}{2}\right)}{\pi d} + \frac{q}{p} \frac{2}{(2cp)^2 - (\pi d)^2}\right.$$

$$\times\left[2cp\sin\left(\frac{\pi d}{2}\right)-\pi d\sin(cp)\right]+\left(1-\frac{q^2}{p^2}\right)\frac{\pi d}{(2cp)^2-(\pi d)^2}$$

$$\times\left[\cos(cp)-\cos\left(\frac{\pi d}{2}\right)\right]-\frac{2(-1)^d}{(2cq)^2+(\pi d)^2}\left[2cq\sin\left(\frac{\pi d}{2}\right)-\pi d\cos\left(\frac{\pi d}{2}\right)\right.$$

$$\left.\left.+\pi d\exp(-cq)\right]\right\},$$

$$N_m^2=\frac{(p^2+q^2)(\bar{t}+q^{-1}+h^{-1})}{2p^2},$$

$$h=\sqrt{\beta_m^2-n_c^2k_0^2},$$

$$p=\sqrt{n_f^2k_0^2-\beta_m^2},$$

$$q=\sqrt{\beta_m^2-n_s^2k_0^2},$$

$$k_0=\frac{2\pi}{\lambda_0},$$

where p, q, h – propagation constants in propagation directions in substrate, film and coat, respectively,
n_f, n_s, n_c – refractive indices of the film, substrate and coat, respectively,
d – integer denoting the Bragg scattering order,
m – waveguide mode order,
λ_0 – wavelength in vacuum.

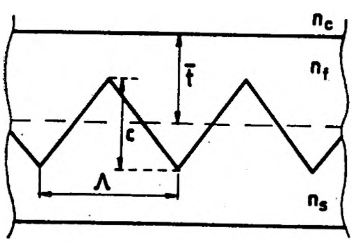

Fig. 9. Triangular grating

Other parameters are shown in Fig. 9.

In this case the behaviour of coupling coefficient K is analogous to that for rectangular grating, but in general the values of K for the same grating depth c, the period of the grating Λ and the effective thickness $\bar{t}$ are smaller (see Figs. 10 and 11).

Now, the magnitude of the coupling coefficient K in the considered structures is known and we know how this coefficient depends upon geometrical

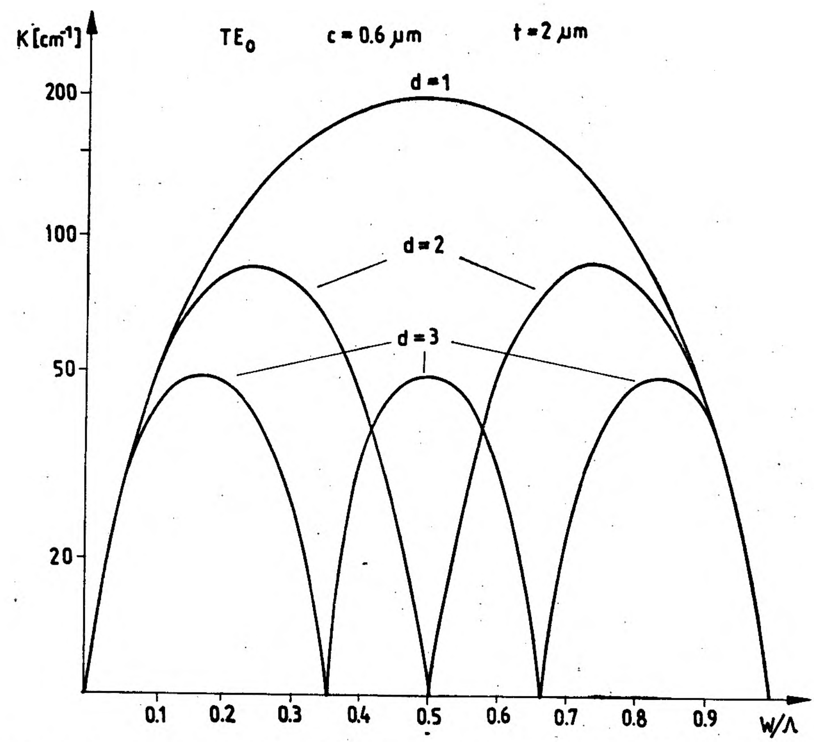

Fig. 7. Coupling coefficient K vs. W/Λ for the first three Bragg orders

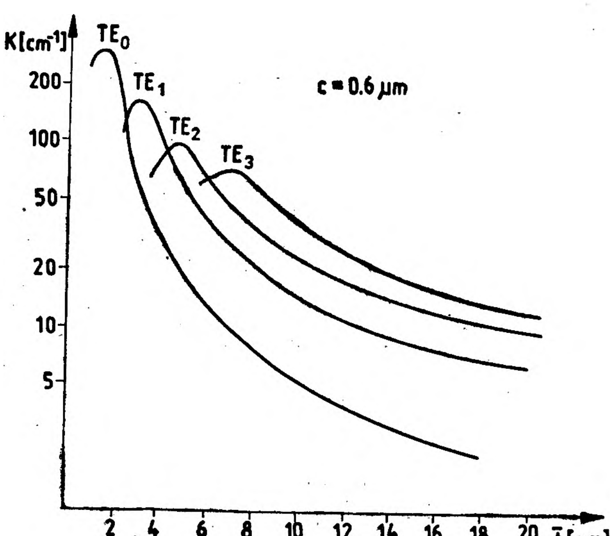

Fig. 8. Coupling coefficient K vs. effective thickness $\bar{t}$ for the first three TE modes

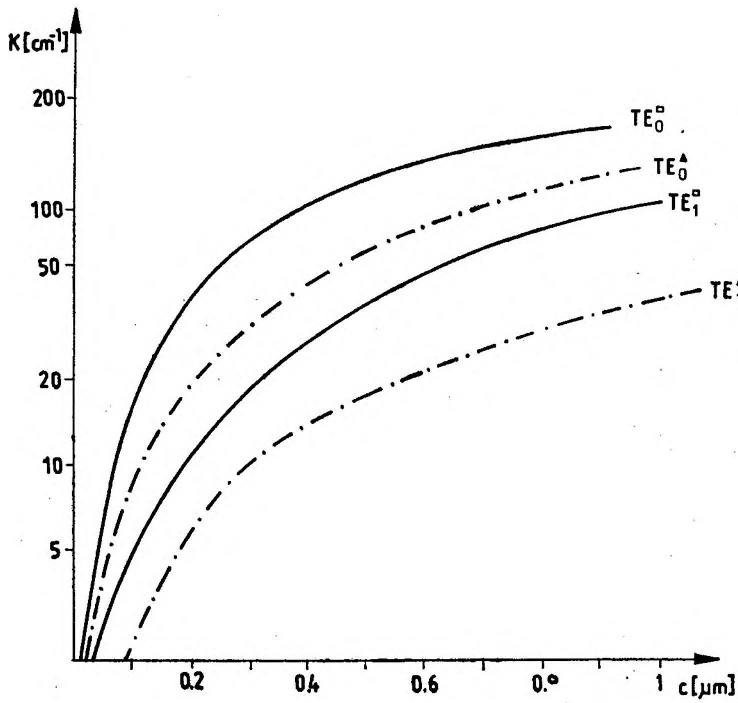

Fig. 10. Coupling coefficient K vs. grating depth c for two types of gratings

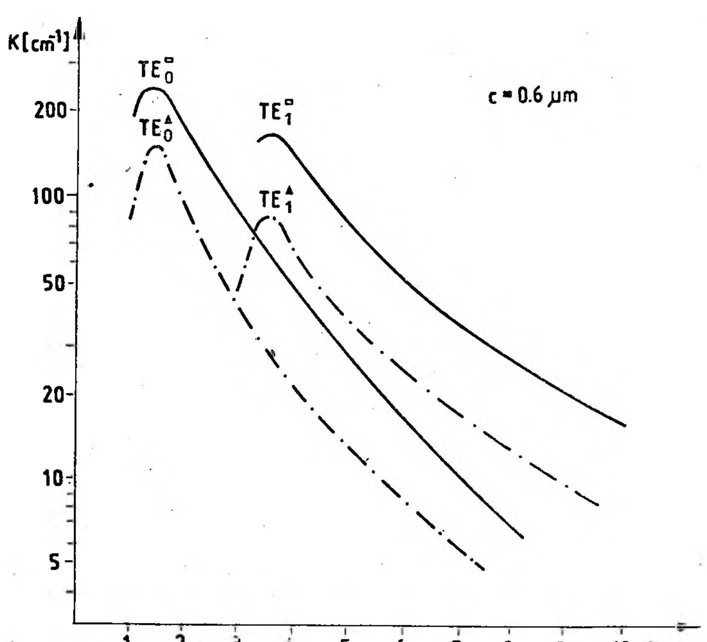

Fig. 11. Coupling coefficient K vs. effective thickness $\bar{t}$ for two types of gratings

parameters of the physical structure. We know, moreover, how threshold gain and frequency of oscillations depend upon the coupling coefficient. Thus, we relate physical parameters of corrugation to characteristics of laser performance.

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