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A GENERALIZED OPTIMIZATION TECHNIQUE FOR STEP DISCONTINUITY IN PLANAR OPTICAL WAVEGUIDES.

طريقة عامة لتحسين الأداء للانقطاع السلمي لموجهات الموجات الضوئية ذات المستوى الواحد

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الخلاصة :
إن الطاقة الضوئية الموجهة والمرسلة عبر وصلة سلمية واقعة بين زوج من موجهات الموجات الضوئية ذات المستوى الواحد تعتمد على التكامل المتداخل لأنماط هذه الموجهات ، وأن أقصى قيمة لهذه الطاقة تحدث عند قيمة معينة للنسبة بين سمك الموجهه وطول الموجة ، وهذه النسبة لا يمكن حسابها تحليليا ، وقد بينا في هذا البحث أن أقصى إرسال للطاقة يعتمد على جزء من التكامل المتداخل الممتد عبر الارتفاع السلمي فقط ، وأيضا بينا أن أقصى إرسال للطاقة يحدث عندما يكون سمك هذين لموجهين للموجات الضوئية متساويا.
وقد مكنا هذا من وضع صيغة عامة لتحسين الإرسال للموجات الموجهة عبر هذه الوصلات السلمية.

Abstract:
The guided optical energy transmitted across a step junction between two planar optical waveguides depends on the overlap integral of the modes of these guides. The maximum guided transmitted power occurs at a certain value of the ratio "guide thickness/wavelength". This ratio cannot be calculated analytically. We have shown that maximum transmission depends on that part of the overlap integral extending over the step height only. We have shown also that maximum transmission occurs when the two guides have equal effective thicknesses. This enables us to formulate the optimization of the guided wave transmission across the junction in a generalized manner such that the specific values of the opto-geometric parameters of the two guides are irrelevant.

I-Introduction:

The concept of integrated optics was born three decades ago with the development of guided waves optical communications. The major problem of fiber optics transmission was the signal attenuation and dispersion due to propagation, which imply the use of repeaters to reformat and amplify the optical signals after long propagation distances. The solution to these problems, offered by bulky classical optics components, are unsatisfactory until Miller [1] suggested another solution based on integrated all-optical components fabricated on a single chip, with optical waveguides connecting them. Consequently, waveguides with different opto-geometrical characteristics (fabricated on the same substrate) are connected together.

The transfer of guided optical energy at the junction between two dissimilar waveguides is accompanied by some loss of energy. The amount of such loss depends on the geometrical and optical parameters of each waveguide (dimensions, refractive indices, etc…). The importance of maximizing the transmission of the guided energy from one guide to another, and minimizing the energy loss is therefore obvious. The theoretical and experimental studies on step waveguide junctions are so extensive. Unfortunately, the theoretical analysis of waveguide junctions is usually very involved and eventually leads to complicated techniques like: Weiner-Hoph [2], residue-calculus [3], integral equations [4] and Green's function [5]. However, some less involved methods like: mode matching [6], beam propagation method (BPM) [7] and polynomial expansion [8] are very useful and give acceptable accurate results for a wide class of waveguide junctions. In spite of the huge efforts devoted to the problem of planar waveguide discontinuities, there is no generalized treatment of that problem, especially when we need to "optimize" the step discontinuity, for example when we seek maximum transmitted guided energy or minimum scattered energy. Because none of the available techniques can expect or predict "when" the conditions of maximum transmitted guided energy or minimum scattered energy occur. For example, it is well known that the transmitted guided energy at a step discontinuity reaches a maximum value at a certain ratio of the "step height/wavelength". This ratio is not known a priori. .

Marcuse [9] applied the mode matching technique in the analysis of the radiation loss of step discontinuities in planar optical waveguides. He found that, as we stated before, there is an optimum wavelength at which the radiation loss is minimum. Many authors [10-15] found the same behavior (point of minimum radiation loss) for optical waveguide junctions.

In this paper , we present a novel optimization method that can deal with step discontinuities without the need to specify the numerical values of the opto-geometric parameters of the step , i.e. a generalized optimization method .

II- Theoretical Formulation:

Figure 1 depicts two dissimilar asymmetric waveguides "1" and "2" which are butt-jointed at the plane $z=0$.

We assume that the cover, film and substrate refractive indices of the waveguides are n_c, n_f and n_s respectively. The film thicknesses are d_1 and d_2. This step is of practical importance because it is very suitable in modeling planar waveguide junctions between two waveguides fabricated on the same substrate (a situation which is frequently encountered in the manufacturing of planar integrated optical components).

For simplicity, we assume that the waveguides are single-mode. The analysis will be carried out for the TE case and the extension to TM case is systematic. Accordingly, a TE mode propagating from $z=-\infty$ in the waveguide "*1*" is incident on the waveguide "*2*" at the junction plane $z=0$. This mode will excite in the backward direction ($z\leq 0$) a guided TE mode and a continuum of TE radiation modes [16,17,18]. The incident mode will excite also in the forward direction ($z\geq 0$) a forward guided TE mode and a continuum of TE radiation modes in wave guide "2". The radiation modes are expressed in the form of Fourier integrals along the transverse wavenumber axis as pointed out by [9,19]. The field components of the TE modes are E_y, H_x and H_z where the subscripts x, y and z denote the direction of these components, while "*E*" and "*H*" denote the electric and magnetic field respectively. The time dependence of the electromagnetic fields is $e^{j\omega t}$ and it will be suppressed throughout the paper. The z-dependence of the guided modes in the guides "*1*" and "*2*" are $e^{-j\beta_1 z}$ and $e^{-j\beta_2 z}$ respectively. The total electric field E_1 in the region $z\leq 0$ is the sum of incident guided mode, the reflected guided mode and the reflected radiation modes. It is written as:

$$E_1 = E^i_y(x) + c_r E^i_y(x) + \int_0^\infty q_r(k_x) \cdot e^r_y(x,k_x) \cdot dk_x \tag{1}$$

where the subscripts or the superscripts "*i*" and "*r*" refer to the incident and reflected fields respectively, and c_r is the reflection coefficient of the backward guided mode while $q_r(k_x)$ is the reflection coefficient of the backward radiation mode e^r_y belonging to guide "1" at the transverse wavenumber k_x ($k_x = \sqrt{k_o^2 - \beta_{rl}^2}$ where $k_o=2\pi/\lambda_o$ is the free-space wavenumber and λ_o is the free-space wavelength) and β_{rl} is the propagation constant of the backward radiation mode (the z-component of the wave vector in the film). Similarly, the total electric field E_2 in the region $z\geq 0$ is given by:

$$E_2 = c_t E^t_y(x) + \int_0^\infty q_t(k_x) \cdot e^t_y(x,k_x) \cdot dk_x \tag{2}$$

where E^t_y is the electric field intensity of the transmitted guided mode whose excitation coefficient (transmission coefficient) is c_t, while $q_t(k_x)$ is the transmission coefficient of the forward radiation mode e^t_y at the transverse wavenumber k_x. The integrals in the right-hand-side of the last two equations represent the radiation modes continuum in both waveguides (i.e. for $z\leq 0$ and $z\geq 0$). Similarly, the total magnetic fields H_1 for $z\leq 0$ and H_2 for $z\geq 0$ are given by:

$$H_1 = H^i_x(x) + c_r H^i_x(x) + \int_0^\infty q_r(k_x) \cdot h^r_x(x,k_x) \cdot dk_x \tag{3}$$

and

$$H_2 = c_t H_x^t(x) + \int_0^{\infty} q_t(k_x)\cdot h_x^t(x,k_x)\cdot dk_x \qquad (4)$$

The magnetic field intensity of the radiation modes in the regions $z\le 0$ and $z\ge 0$ are h^r_x and h^t_x respectively. Noting that Maxwell's equations allows us to write:

$$H_x = \frac{-j}{\omega\mu}\cdot\frac{\partial E_y}{\partial Z} \qquad (5)$$

where ω is the radial frequency and μ is the magnetic permeability which is assumed to be equal to the free space magnetic permeability μ_o. The propagation constants of the guided modes in both waveguides will be denoted by β_1 and β_2 while those of the radiation modes are β_{ri} and β_{rt}. The continuity of the transverse components of the electric and magnetic fields at $z=0$ (taking the last equation into account) result in the following two equations:

$$E_y^i(x)+c_rE_y^i(x)+\int_0^{\infty} q_r(k_x)\cdot e_y^r(x,k_x)\cdot dk_x = c_tE_y^t(x)+\int_0^{\infty} q_t(k_x)\cdot e_y^t(x,k_x)\cdot dk_x \qquad (6)$$

$$-\beta_1 E_y^i(x)+\beta_1 c_r E_y^i(x)+\int_0^{\infty}\beta_{ri}q_r(k_x)\bullet e_y^r(x,k_x)\bullet dk_x = -\beta_2 c_t E_y^t(x)-\int_0^{\infty}\beta_{rt}q_t(k_x)\bullet e_y^t(x,k_x)\bullet dk_x - \qquad (7)$$

The transverse distribution of the guided mode field can be obtained by solving the wave equation in the three regions: cover, film and substrate, then satisfying the boundary conditions at the upper and lower interfaces of the film [13,17]. The resulting eigenvalue equation for the propagation constant β is then solved numerically. For the guided TE mode, the transverse distribution of the electric field is given by:

$$\left.\begin{aligned} E_y &= A_l e^{-\alpha_{cl}x} && \text{for } x\ge 0\\ &= A_l[\cos(\kappa x)-\frac{\alpha_{cl}}{\kappa_l}\sin\kappa_l x] && ,-d_l\le x\le 0\\ &= A_l[\cos(\kappa_l d_l)+\frac{\alpha_{cl}}{\kappa_l}\sin\kappa_l d_l]\cdot e^{\alpha_{sl}(x+d_l)} && ,x\le -d_l \end{aligned}\right\} \qquad (8)$$

where:

$\alpha_{c1}=\sqrt{\beta_1^2-k_o^2n_c^2}$, $\kappa_1=\sqrt{k_o^2n_f^2-\beta_1^2}$, and $\alpha_{s1}=\sqrt{\beta_1^2-k_o^2n_s^2}$. A is an arbitrary constant amplitude which can be normalized such that the power carried by a guided mode is unity. Accordingly A is given by:

$$A_l = \frac{2\kappa\sqrt{\omega\mu_o P}}{\sqrt{\beta_l\left[d_l+\frac{1}{\alpha_{cl}}+\frac{1}{\alpha_{sl}}\right]\bullet\left[\kappa_l^2+\alpha_{cl}^2\right]}} \qquad (8\text{-a})$$

where the power carried by the mode is:

$$P = \frac{\beta_l}{2\omega\mu_o}\int_{-\infty}^{\infty} E_y(x)\cdot E_y^*(x)dx = 1 \qquad (9)$$

The asterisk denotes the complex conjugate. The unknown propagation constant β_l is the solution of the following eigenvalue equation:

$$\kappa_l d_l - \tan^{-1}(\frac{\alpha_{sl}}{\kappa_l}) - \tan^{-1}(\frac{\alpha_{cl}}{\kappa_l}) = m\pi \qquad (9\text{-a})$$

where "m" is an integer: the mode order.

III- Approximate Solution for the Transmission and Reflection Coefficient:

It is well known [6, 8, 9, 12] that an exact solution to Eqns. (6) and (7) is obviously impossible since we have two equations and four unknowns c_r, c_t, q_r and q_t. However, an approximate solution can be obtained by neglecting the reflected radiation modes (i.e. neglecting $q_r(k_x)$). This approximation is acceptable and justified [9] if the amplitude of the guided reflected mode c_r is much less than the amplitude of the guided transmitted mode c_t. In that case $q_r(k_x)$ will never exceeds c_r. Such approximation is valid in both cases:

Large step size : in this case $q_t(k_x) >> q_r(k_x)$, that is the radiation loss in the forward direction is the dominant one.

Small step size: in this case the modes of both guides "*1*" and "*2*" are nearly the same, i.e. they are almost orthogonal to each other, and hence the projection of the guided transmitted mode $E_y^t(x)$ on the reflected radiation modes $q_r(k_x)e_y^r(x,k_x)$ is negligible. This will simplify very much the solution of (6) and (7) because if we take the scalar product of both sides of (6) with the complex conjugate magnetic field of the guided transmitted mode $H_x^{t*}(x)$, that is, multiplying both sides of (6) with $H_x^{t*}(x)$ and integrating over x from $-\infty$ to ∞ and taking (5) into account (i.e. $H_x^{t*}(x) = (-\beta_2 / \omega\mu_o)E_y^{t*}(x)$) we obtain:

$$\frac{\beta_2(1+c_r)}{\omega\mu_o}\int_{-\infty}^{\infty} E_y^i(x)\cdot E_y^{t*}(x)dx = c_t\cdot\left[\frac{\beta_2}{\omega\mu_o}\int_{-\infty}^{\infty} E_y^t(x)\cdot E_y^{t*}(x)dx\right] \quad (10)$$

It is important to note that the guided transmitted mode is orthogonal to the forward radiation modes (since they belong to the same guide "*2*", i.e. the scalar product of $E_y^{t*}(x)$ and $\int_{-\infty}^{\infty} q_t(k_x)\cdot e_y^t(x,k_x)dk_x$ is zero). Recalling that the term between the brackets in the right-hand side of (10) is twice the power carried by a guided mode (c.f. eq. (9)), so we can write (10) as follows:

$$c_t = \frac{\beta_2(1+c_r)}{2\omega\mu_o}\int_{-\infty}^{\infty} E_y^i(x)\cdot E_y^{t*}(x)dx \quad (11)$$

Similarly, multiplying (7) by $E_y^{t*}(x)$ and integrating over the whole cross section of the junction plane we obtain:

$$\frac{\beta_1(1-c_r)}{\omega\mu_o}\int_{-\infty}^{\infty} E_y^i(x)\cdot E_y^{t*}(x)dx = c_t\cdot\left[\frac{\beta_2}{\omega\mu_o}\int_{-\infty}^{\infty} E_y^t(x)\cdot E_y^{t*}(x)dx\right] \quad (12)$$

This equation gives:

$$c_t = \left[\frac{\beta_1(1-c_r)}{2\omega\mu_o}\int_{-\infty}^{\infty} E_y^i(x)\cdot E_y^{t*}(x)dx\right] \quad (13)$$

Equations (11) and (13) can be solved for c_t and c_r :

$$c_r = \frac{\beta_1-\beta_2}{\beta_1+\beta_2} \quad (14)$$

$$c_t = \frac{\beta_1\beta_2}{(\beta_1+\beta_2)\omega\mu_o}\int_{-\infty}^{\infty} E_y^i(x)\cdot E_y^{t*}(x)dx \quad (15)$$

From the last two equations we can readily calculate the guided reflected and transmitted powers P_r and P_t :

$$\left.\begin{aligned} P_t &= c_t^2 \\ P_r &= c_r^2 \end{aligned}\right\} \quad (16)$$

and hence the scattered power P_s lost by radiation at the junction plane is:

$$P_s = 1 - c_r^2 - c_t^2 \quad (17)$$

As stated before, P_s reaches a minimum value at a certain wavelength λ_o (a well known characteristic result of symmetric and asymmetric junctions). To check such a result we considered a junction with $d_2/d_1 = 0.5$, $d_1 = 4\mu m$, $n_c = 1$, $n_f = 1.51$ and $n_s = 1.5$ where both guides are single-mode in the wavelength range:

$$\lambda_{c11} \le \lambda \le \lambda_{co2} \quad (18)$$

where λ_{c11} is the cutoff wavelength of the first order mode (m=1) of the thick waveguide (guide "*1*") *While* λ_{c02} is the cutoff wavelength of the fundamental mode (m=0) of the thin waveguide (guide "*2*"). These wavelengths are given by:

$$\lambda_{c02}=\frac{2\pi d_2\sqrt{n_f^2-n_s^2}}{tan^{-1}\sqrt{\frac{n_s^2-n_c^2}{n_f^2-n_s^2}}} \tag{19}$$

and:

$$\lambda_{c11}=\frac{2\pi d_1\sqrt{n_f^2-n_s^2}}{\pi+tan^{-1}\sqrt{\frac{n_s^2-n_c^2}{n_f^2-n_s^2}}} \tag{20}$$

Accordingly both guides are single-mode over the wavelength range $0.96\mu m \le \lambda \le 1.54\mu m$. Fig. 2, depicts the variations of P_t , P_r and P_s as function of the dimensionless parameter $k_o d_1$ where k_o is the free space wavenumber $2\pi/\lambda$. A minimum of the power lost by radiation P_s occurs at $k_o d_1 \approx 21.8$ which corresponds to a wavelength $\lambda_o \approx 1.15\mu m$. From that figure we remark that the peak of the guided transmitted power P_t occurs at the same λ_o . But the peak of the reflected guided power P_r does *not* occur at the same λ_o.

One of the main results in this paper is to find out the crucial factor which is responsible for the peak in P_t (or c_t). Referring to equation (15), c_t is equal (apart from a multiplicative constant factor $1/\omega\mu_o$) to the product of two terms: the first one is $\beta_1\ \beta_2/\ \beta_1+\ \beta_2$, and the second one is the overlap integral I between $E_y^I(x)$ (the transverse pattern of the incident guided mode) and $E_y^{I^*}(x)$ (the transverse pattern of the transmitted guided mode). The first term does not have a maximum as the normalized wavenumber $k_o d_1$ is varied. The second term (the overlap integral) must be considered *carefully*.

If we write the integration I of the function $S(x) = E_y^I(x)\cdot E_y^{I^*}(x)$ along the whole transverse coordinate $-\infty \le x \le \infty$ as the sum of four integrals:

$$I=\{\ \int_{-\infty}^{-d_1}+\int_{-d_1}^{-d_2}+\int_{-d_2}^{0}+\int_{0}^{\infty}\ \}.S(x)dx \tag{21}$$

These integrals will be denote by I_1, I_2, I_3 and I_4 respectively. Fig. 3 represents the variation of these integrals and the transmission coefficient c_t as function of the normalized wavenumber $k_o d_1$.
(the guides have the same opto-geometrical characteristics as those corresponding to guides of Fig. 2).
It is obvious from Fig.3 that the contribution of the fourth integral I_4 to c_t is negligible (of the order 10^{-4}) and its peak is far from the peak of c_t. Also the peak of I_1 is far from the peak of c_t , while I_3 increases monotonically with $k_o d_1$. It remains the integral I_2 over the step height from $-d_1$to $-d_2$, which has its peak at $k_o d_1$=21.43 which corresponds to a wavelength λ=1.17μm while the peak of c_t occurs at λ=1.15μm which is too close to 1.17μm. This means that the step height is the dominant factor which determines the amount of the maximum guided power transmitted across the step discontinuity. And since the guided transmitted power increases as the patterns (transverse distribution of the electromagnetic fields) of the incident and transmitted modes become close to each other, this lets us to think about the equality of the effective thickness of both guided modes: d_{eff1} and d_{eff2} which are leads as:

$$d_{eff1} = (1/d_1) + (1/\alpha_{c1}) + (1/\alpha_{s1}) \tag{22}$$
$$d_{eff2} = (1/d_2) + (1/\alpha_{c2}) + (1/\alpha_{s2}) \tag{22-a}$$

where α_{c1} and α_{c2} are the decay rates of the evanescent tails of the guided modes in the cover region (for guide 1 and guide 2 respectively). Similarly α_{s1} and α_{s2} are the decay rates of the evanescent tails of the guided modes in the substrate. Fig. 4 depicts the variations of d_{eff1}, d_{eff2} and c_t as function of the normalized wavenumber $k_o d_1$. Both widths are equal at $k_o d_1$=21.27 (point *A*) while the peak of c_t occurs at $k_o d_1$=21.73 (point *B*). The relative difference in c_t at these normalized wavumbers is of the order 0.08%. This negligible difference is one of the important results of this paper. Namely, the waveguide junction is optimal when the effective thicknesses of the fundamental modes of both guides are equal.

IV- Generalized Optimization of the Junction Discontinuity:

Starting with the normalized frequency V defined as:

$$V = k_o d\sqrt{n_f^2 - n_s^2} \tag{23}$$

and the normalized effective waveguide thickness D_e:

$$D_e = k_o d_{eff}\sqrt{n_f^2 - n_s^2} \tag{24}$$

we recall that the waveguide asymmetry parameter "a" and the normalized effective mode index "b" are defined as:

$$a = \frac{n_s^2 - n_c^2}{n_f^2 - n_s^2} \tag{25}$$

$$b = \frac{n_e^2 - n_s^2}{n_f^2 - n_s^2} \tag{26}$$

where $n_e = \beta / k_0$ is the mode effective index. According to these four equations, the normalized dispersion relation for the mth order mode (i.e. "b" as a transcendental function of "V") takes the form:

$$V\sqrt{1-b} = m\pi + tan^{-1}\sqrt{b/(1-b)} + tan^{-1}\sqrt{b+a/(1-b)} \tag{27}$$

It is worthwhile to note that normalized dispersion diagram [14] is obtained by solving numerically the previous equation to get "b" as function of "V".

The mode cutoff corresponds to b=0, i.e. the normalized cutoff frequency V_{cm} of the mth order mode is given by:

$$V_{cm} = V_{co} + m\pi \tag{28}$$

where V_{co} is the normalized cutoff frequency of the fundamental mode (m=0) which, according to equation (27), is given by:

$$V_{co} = tan^{-1}\sqrt{a} \tag{29}$$

Finally, the normalized effective waveguide thickness D_e can be written as an implicit function of V (since b is a transcendental function of V) in a form [14] equivalent to that one given in Eqn. (24):

$$D_e = V + \frac{1}{\sqrt{b}} + \frac{1}{\sqrt{b+a}} \tag{30}$$

Figure 5 presents the numerical solution of (30), i.e. $D_e(V)$ for the fundamental mode. It is crucial to note that there are two values V_1 and V_2 (i.e. two different waveguides with different core thicknesses "d", c.f. equation.[23]) corresponding to one value of D_e . This is also shown in Fig. 6 for different values of the asymmetry parameter "a". This means that it is always possible to find two different waveguides having equal effective waveguide thicknesses, i.e. an optimum waveguide junction, without an *a priori* knowledge of the specific numerical values of the opto-geometric parameters of the waveguides forming the junction. The normalized optimization diagram is therefore obtained by solving a two-fold eigenvalue problem, since we have to search for two eigenvalues: b_1 and b_2 which must satisfy the following transcendental equation:

$$D_e(V_1) = D_e(V_2) \tag{31}$$

or equivalently:

$$V_1 + \frac{1}{\sqrt{b_1}} + \frac{1}{\sqrt{b_1+a}} = V_2 + \frac{1}{\sqrt{b_2}} + \frac{1}{\sqrt{b_2+a}} \tag{32}$$

It is important to note that b_1 is function of V_1 (through the eigenvalue equation (27)) and similarly for b_2. Figure 6 shows a sample of a family of the normalized optimization diagrams for different asymmetry parameter "a". Thus, given one waveguide with certain V_1 (and hence knowing b_1 by solving the eigenvalue Eqn. (27)); the other optimum guide forming the junction has a "V_2" (noting that b_2 is function of V_2) which can be found from the diagram.

V- Conclusions:

Using the mode-matching technique we have shown that the peaks of the transmission coefficient and the mode overlap integral over the step height occur almost at the same effective waveguide thickness. Furthermore, it was shown that there exist always two dissimilar waveguides having the same effective thickness (as shown in Fig.5). Consequently, the condition for an optimal junction is formulated by solving a two-fold transcendental equation. This allows the generation of a family of normalized optimization diagrams (Fig.6) which can be used in the design of planar optical waveguide components for integrated optics.

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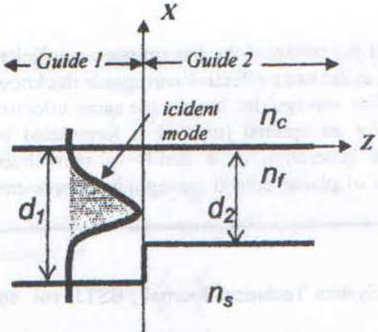

Fig. 1- An asymmetric waveguide junction.

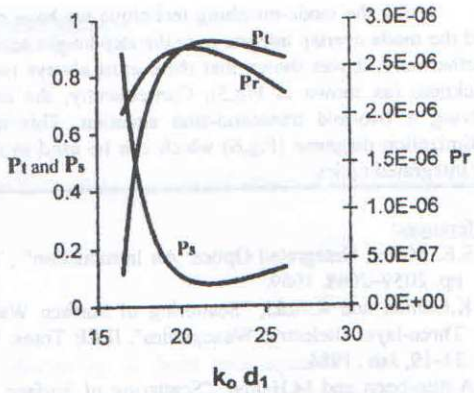

Fig. 2 – Variation of the guided transmitted and reflected power P_t, P_r and the power lost P_s as function of $k_o d_1$.

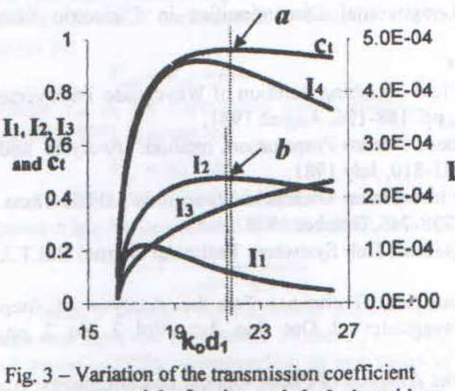

Fig. 3 – Variation of the transmission coefficient c_t and the four integrals I_1, I_2, I_3 and I_4 as function of the normalized waveguide thickness $k_o d_1$. The peaks *a* and *b* of c_t and I_2 occur almost at same value of $k_o d_1$

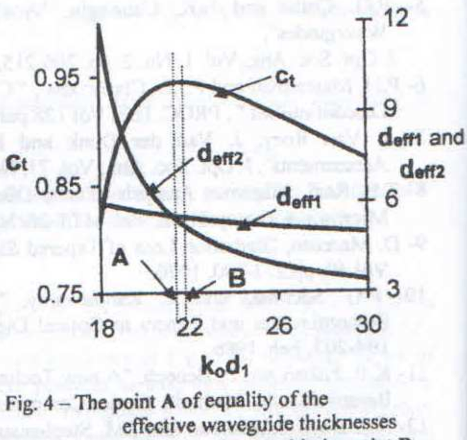

Fig. 4 – The point A of equality of the effective waveguide thicknesses coincides almost with the point B of maximum transmission coefficient c_t

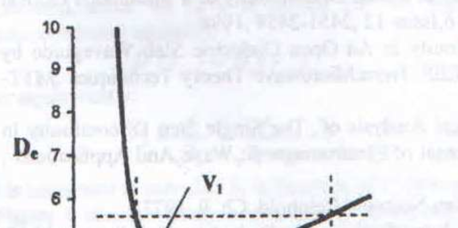

Fig. 5 – Two different values of V (V_1 and V_2) having the same thickness D_e.

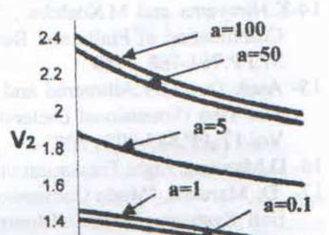

Fig. 6 - Generalized optimization diagram