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# OPTICAL BISTABILITY OF A PRISM-COUPLED NONLINEAR SLAB WAVE GUIDE

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## Abstract

We describe the bistable behaviour of a prism-coupled nonlinear double-boundary slab waveguide. We show that the bistable light reflection is possible in the system when the mismatch from the condition of the optimal waveguide excitation is adequately chosen. A system based on this configuration is proposed to achieve a high-contrast bistable switch.

*Keywords:* nonlinear optical waveguide, optical bistability, prism-coupling.

## 1. Introduction

The properties of a nonlinear optical system depend on the electric field strength or intensity of the light incident upon it. Under appropriate conditions a nonlinear system can exhibit a threshold characteristic so that a suitable optical device can be made to perform logic operations. A system is said to be optically bistable if there exist two stable output intensity possibilities for the same input intensity. Since the discovery of optical bistability (OB), observed for the first time in 1976, a large number of methods were proposed for realization of a bistable system [1]. The main directions of the research works are presently to reduce the device sizes and the switching power, and to improve the switching speed. For the realization of these requirements the most attractive optical bistable devices are the nonlinear waveguide-type systems (coupled waveguides, waveguides excited by nonlinear Bragg diffraction, etc.) [2]. Among them, the structures formed by nonlinear slab waveguides represent a special class. The properties of nonlinear optical waves propagating in a dielectric slab geometry have been studied intensively by using analytical and numerical methods [3], [4].

Recently, AVRUTSKII et al. [5] reported on the optical bistability under the excitation of a nonlinear corrugated waveguide. They derived analytical expressions describing the bistability and formulated the existence criteria, in accordance with the former experimental results [6]. In this paper, we generalize this method and describe the bistable behaviour of a prism-coupled nonlinear slab waveguide. We show that in the bistable regime in a dissipative nonlinear waveguide the 'switch-on' state corresponds to a small reflection (when the guided power is large), and the 'switch-out' state corresponds to a large reflection (when the guided power is small).

## 2. Basic Relations

The transfer of light from a radiation source into an optical slab waveguide is done via radiation coupling. The most efficient methods of coupling are based on techniques in which electromagnetic power flux runs parallel to the guide and gradually leaks into it. The *prism-coupler* (*Fig. 1*) operates through a distributed coupling by frustrated total reflection at the base of a high-index of refraction prism when pressed down onto a film (or strip) waveguide. The main advantages are a near 100% coupling efficiency which is achieved by a proper construction, a mode selective coupling, and an easy realization – at least for film waveguides and moderate coupling efficiencies.

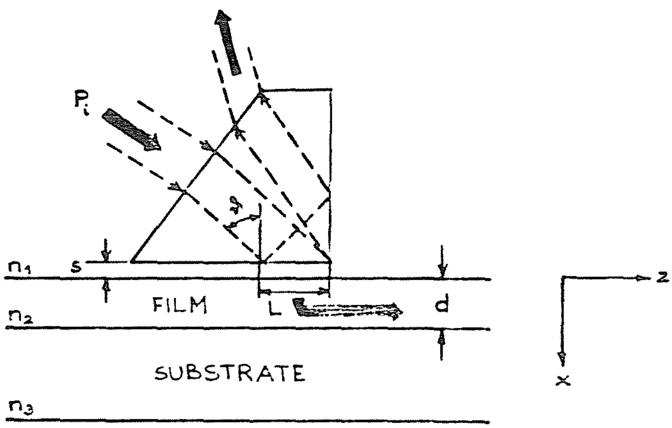


*Fig. 1.* Prism coupling to a slab waveguide

If the input beam is totally reflected at the base of the prism, a standing-wave distribution (in x-direction) within the prism and an exponentially decaying field in the air gap are generated, which propagates with a phase velocity [7–11]

$$v_p = c/(n_p \sin\vartheta) \tag{1}$$

parallel to the waveguide ($c$ = vacuum light velocity). For a sufficiently narrow gap between prism and waveguide, the field underneath the prism base reaches into the waveguide and excites a waveguide mode, when this one propagates synchronously, i.e. with the same phase velocity $v_p = c/n_{\text{eff}}$. Here, $n_3 < n_{\text{eff}} < n_2$ is the effective index of a waveguide mode. Then we have coupling angles $\vartheta$ to waveguide modes within the range

$$n_3/n_p < \sin\vartheta < n_2/n_p \; . \tag{2}$$

The width $s$ of the coupling gap must be extremely small for efficient coupling, and there exists an optimum coupling length $L$ since the excited waveguide mode couples back into the prism. Therefore, the input beam must be positioned near the right end of the prism.

It can be proved [7–8] that the power density $P$ of the radiation propagating in the waveguide is

$$P = \frac{\beta P_i}{(n_p \sin\vartheta - n^*)^2 + a^2}, \tag{3}$$

where $n_p$ – the index of prism; $\vartheta$ – the angle of incidence at the prism-film interface; $n^*$ – the real part of the effective index of refraction; $a = (\alpha_{\text{rad}} + \alpha_{\text{dis}})/2k$ – an expression containing the radiation and dissipative losses; $k = 2\pi/\lambda$ – the wave-number, $P_i$ – the input power density. It must be noted that the coupling coefficient $\beta$, the effective index of refraction and the losses depend on the parameters of the prism-coupler in a very complicated manner and they can be evaluated only by computing methods in each practical case. Fortunately, these calculations are not needed for our investigations. We assume that the guided power density $P$ affects on the real part of the effective index $n^*$ in a linear form:

$$n^* = n_0^* + \gamma P \; . \tag{4}$$

It is important to note that *Eq.* (4) is valid only for relatively small power densities $P$, or for small coefficients of nonlinear refraction. In case of stronger nonlinearity the propagation constant depends on the power density $P$ in a complicated manner and can exhibit bistable character in some cases [12]. When the waveguide is excited on condition that the *Eqs.* (3) and (4) are fulfilled the possibility of the optical bistability arises.

So, in our work the foolowing expression plays a fundamental role

$$P = \frac{\beta P_i}{(\Delta - \gamma P)^2 + a^2} \; , \tag{5}$$

where $\Delta = n_p \sin\vartheta - n_0^*$ - the detuning at low power levels in the waveguide. It is assumed that the dissipative losses are parameters of the waveguide and do not vary with $P$.

## 3. The Bistability Effect

The *Eq.* (5) describes the *bistability* under the excitation of the waveguide. It represents a 3-rd order equation for $P$:

$$P^3 - 2\Delta P^2/\gamma + (\Delta^2 + a^2)P/\gamma^2 = \beta P_i/\gamma^2 . \tag{6}$$

This equation can be solved in a closed form, however, for the determination of the basic parameters characterizing the bistability this procedure is not necessary. Let's denote the left side of *Eq.* (6) by $f(P)$ and investigate its extremum properties. $f(P)$ is monotonically varying for $\mathrm{d}f/\mathrm{d}P \geq 0$, that is

$$\Delta^2 - 3a^2 \leq 0 \tag{7}$$

and has an extremum when

$$\Delta^2 - 3a^2 > 0 ,$$

or

$$|n_p \sin\vartheta - n_0^*| > \sqrt{3}a . \tag{8}$$

Only the positive values of $P$ have a physical meaning, therefore the existence of extremums for $f(P)$ involves the fulfilment of the condition

$$\Delta/\gamma > 0. \tag{9}$$

The power values for which $\mathrm{d}f/\mathrm{d}P = 0$ are

$$P_{1,2} = [2\Delta \pm (\Delta^2 - 3a^2)^{1/2}]/3\gamma. \tag{10}$$

Substituting *Eq.* (10) into *Eq.* (6) we can get the 'switch-on' and 'switch-out' powers of the bistable optical device under investigation. The guided wave power $P$ as a function of the incident power $P_i$ is plotted in *Fig. 2*. This curve shows a typical bistable character. So we get the 'switch-on' and 'switch-out' powers of the *optical bistable device*:

$$\begin{aligned} P_i^{\uparrow} &= 2[\Delta(\Delta^2 + 9a^2) + (\Delta - 3a^2)^{3/2}]/27\beta\gamma ; \\ P_i^{\downarrow} &= 2[\Delta(\Delta^2 + 9a^2) - (\Delta - 3a^2)^{3/2}]/27\beta\gamma . \end{aligned} \tag{11}$$

The smallest incident power which leads to bistable regime, in the case of $\Delta^2 = 3a^2$ is:

$$P_{i,\min} = 8\sqrt{3}a^3/9\beta\gamma . \tag{12}$$

The evaluation of this expression could be possible only when we know connections between the parameters. Since such closed form relations are not available, we can solve any practical arrangement by numerical methods.

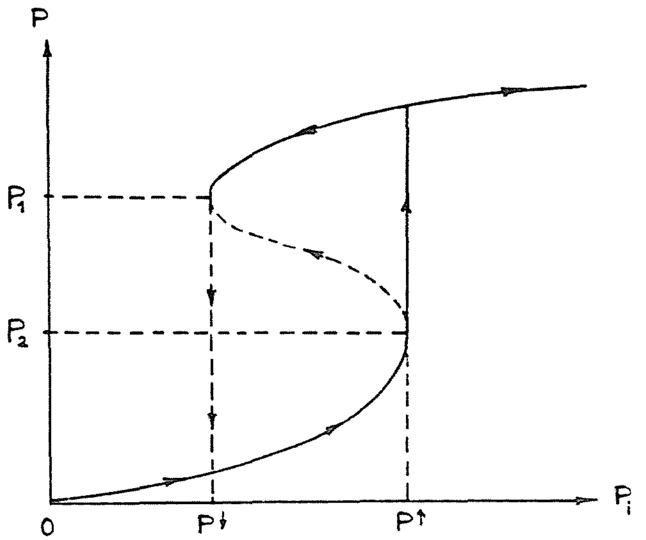


*Fig. 2.* Guided-wave power as a function of the input power

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