Nonlinear wave propagation in an asymmetric converging Y junction

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Nonlinear wave propagation in an asymmetric converging Y junction, which consists of a nonlinear cladding, a linear film, and a linear substrate, is studied. The nonlinear dispersion curves of the successive sections of the Y junction are calculated to be used to illustrate the evolutions of the eigenmodes. The field incident from the nonlinear thinner branch can evolve into the symmetric mode of the stem with a high coupling efficiency. An insertion coupler for a time-multiplexed loop is suggested.

Recently nonlinear waveguide junctions have been investigated extensively for their interesting switching behavior. The self-switching transition changes sharply with its intensity.[1] Furthermore the waveguide X junction is shown to exhibit the capability of switching a light beam by controlling the intensity of another light beam or the relative phase between these two light beams.[2] The studies have led to a growing interest in all-optical switching based on waveguide junctions.[3] Here we use the nonlinear dispersion curves to illustrate the evolutions of the eigenmodes in the converging Y junction, which are verified by the beam-propagation method.[4]

For a symmetric linear Y junction, there is an inherent 50% loss of energy when the eigenmode is coupled from one branch into the stem. For an asymmetric linear Y junction, the eigenmode injected into the thinner branch at a distance from the junction will not transmit to the stem, and the eigenmode injected into the thicker branch away from the junction will propagate to the stem without loss.[5,6]

The structure of the Y junction considered in this Letter is shown in Fig. 1. The cladding is nonlinear, therefore the thinner branch and the stem are nonlinear guides. Light at a wavelength of 1.3 μm is considered. The linear dielectric constants of the substrate, the film, and the cladding are 2.4025, 2.4649, and 2.4025, respectively; the nonlinear coefficient of the cladding $\alpha = 3.3776 \times 10^{-12}$ m^2/V^2. The thickness of the thicker branch and the stem of the Y junction is 2.5 μm, and the thickness of the thinner branch is 1.5 μm; all three guides are single-mode guides. The junction angle is 2 × 0.87 mrad. Such a small angle ensures that the wave propagated in the junction will evolve adiabatically.

The nonlinear TE dispersion curves of five selected sections (positions A, B, C, D, and E in Fig. 1) for symmetric and antisymmetric modes of the Y junction are depicted in Figs. 2(a) and 2(b), respectively.[7] It was pointed out that most of the positively sloped branches are stable,[8] and we concentrate our investigation on the evolution of the guided modes of the stable branches. At position A, the separation between the two branching guides is 6 μm, and the dispersion curve is almost the same as that of the infinite separation between the two guides. Because the separation is sufficiently large, the nonlinear dispersion curve of this five-layered waveguide structure can be treated as the superposition of the dispersion curves of the two individual branches. The dispersion curve of the nonlinear thinner branch is divided into two parts, a symmetric and antisymmetric mode, by the vertical dispersion curve of the linear thicker branch. As the two guides converge, for the symmetric mode, the maximum guided power decreases monotonically, and the cutoff value for effective index increases to a maximum value when the two guides join together, then it decreases owing to the taper of the guide; for the antisymmetric mode, the maximum guided power and the cutoff value for the ef-

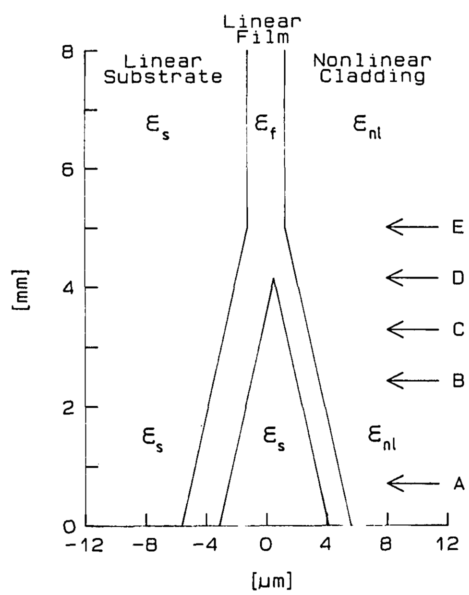
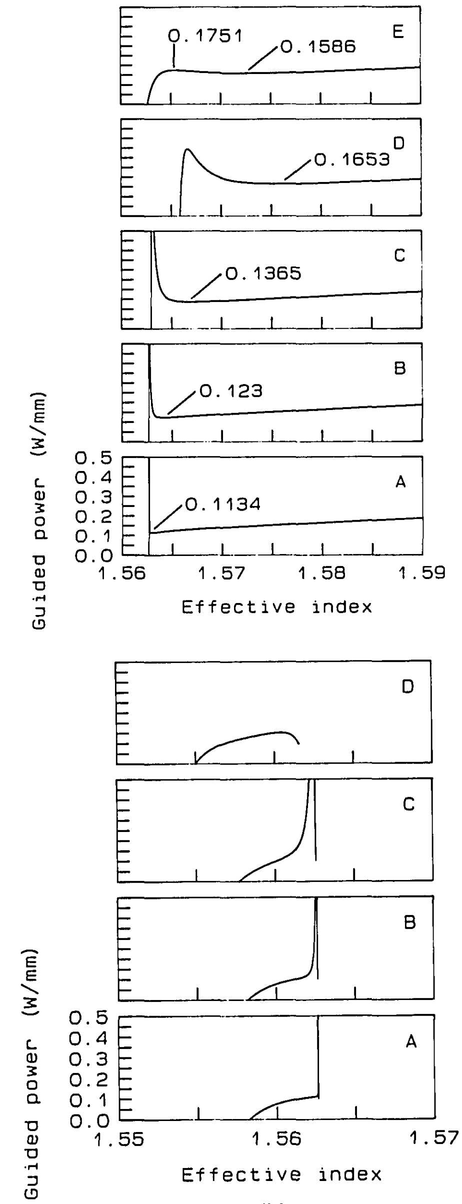


Fig. 1. Schematic structure of the Y junction.



(b)

Fig. 2. (a) Nonlinear dispersion curves of the symmetric mode. (b) Nonlinear dispersion curves of the antisymmetric mode.

fective index decrease monotonically. At position E, the antisymmetric mode is below cutoff.

A light beam injected into the linear thicker branch excites the symmetric mode of the positively sloped vertical part of the nonlinear dispersion curve of the five-layered waveguide structure and evolves adiabatically in the Y junction. When the light beam is injected into the nonlinear thinner branch, depending on its power, it excites either the symmetric or the antisymmetric mode and remains or radiates in the stem.

The other interesting phenomenon is the variation of the minimum guided power of the surface polariton of the TE_0 mode in the Y junction; the minimum power is 0.1653 W/mm at the joint (position D), which is the highest value in the Y junction. For a surface polariton injected into the nonlinear thinner branch whose power is larger than 0.1653 W/mm, it evolves adiabatically in the Y junction. For a light beam injected into the nonlinear thinner guide when the power is high enough to excite a symmetric mode but less than 0.1653 W/mm, the field evolves adiabatically at first, then has an abrupt transition from the surface polariton mode to the symmetric mode at the point where the injected power is less than the minimum guided power of the surface polariton. This phenomenon is called a jump.

Four numerical examples of wave propagation in the converging Y junction calculated by the beam-propagation method are shown to be consistent with the above discussion.

First, a light beam of power 0.165 W/mm is injected into the linear thicker branch. As shown in Fig. 3(a), the light beam evolves adiabatically into the symmetric mode in the Y junction. A light beam

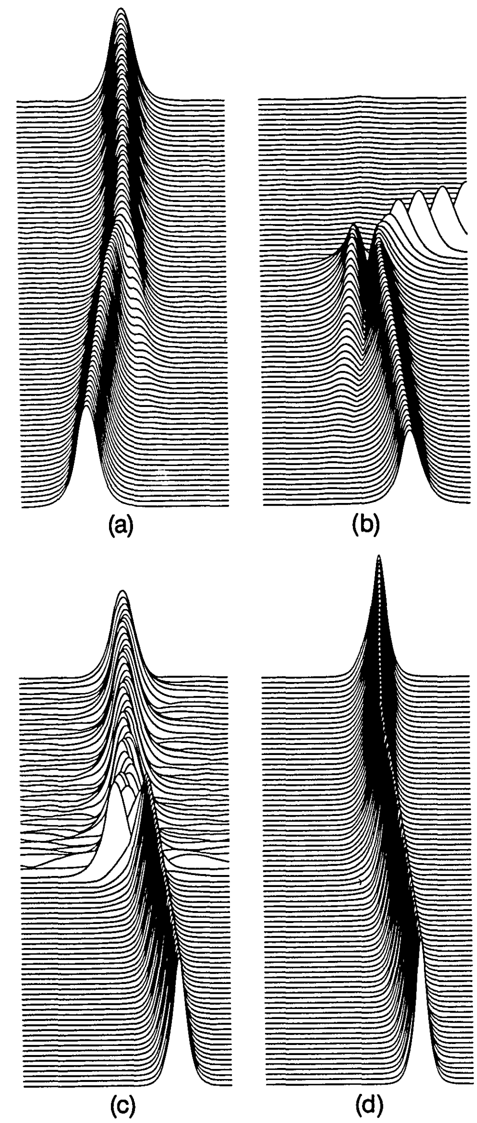


Fig. 3. Field evolutions in the Y junction. (a) Light beam of power 0.165 W/mm is injected into the linear thicker branch. (b) Light beam of power 0.0825 W/mm is injected into the nonlinear thinner branch. (c) Light beam of power 0.165 W/mm is injected into the nonlinear thinner branch. (d) Light beam of power 0.185 W/mm is injected into the nonlinear thinner branch.

of smaller power is injected, and the result is the same. Because the maximum guided power of the stem shown in the dispersion curve is approximately 0.1751 W/mm for the symmetric mode, an injected beam of larger power will not evolve adiabatically but with a large radiation.

Second, three light beams of different powers are injected into the nonlinear thinner branch, and they cause three different evolutions. (i) For guided power less than 0.1134 W/mm, the light beam will evolve into the antisymmetric mode and radiate when the guide is tapered to the single-mode stem. In Fig. 3(b), the light beam of power 0.0825 W/mm is injected; there is no light coupled to the stem. (ii) The power of the incident light beam is in the range of 0.1134–0.1653 W/mm. In Fig. 3(c), the light beam of power 0.165 W/mm is injected; it jumps from the surface polariton to the symmetric mode of the guide near the joint. After the jump, the higher-order modes are excited and propagate together with the symmetric mode, and the power coupling efficiency is approximately 75%. (iii) The guided power is larger than 0.1653 W/mm. The evolution of the light beam of power 0.185 W/mm is shown in Fig. 3(d). The bulge of the field is always in the nonlinear medium during the propagation, i.e., the light beam is maintained in the surface polariton mode when the light beam is injected into the thinner branch to the stem. However, owing to the intrinsic loss of the waveguide and the slight amount of momentum in the transverse direction, the surface polariton will finally jump to the symmetric mode of the stem after a long propagation distance.

In conclusion, for an asymmetric converging Y junction that has a nonlinear cladding in the side of the stem and the thinner branch, the light beam injected into the thinner branch may evolve to the symmetric mode. It is shown that the effective index of the nonlinear thinner branch will be larger than that of the linear thicker branch for an appropriate injected light beam, so the light beam will evolve to the symmetric mode and propagate to the stem with a high coupling efficiency. For a light beam of high injected power, the light beam will maintain itself in the surface-polariton mode from the nonlinear thinner branch to the stem without loss. For a light beam of lesser injected power but high enough to excite the symmetric mode, the light beam will move from the surface-polariton mode to the symmetric mode near the junction point. At low injected power, the light beam will evolve to the antisymmetric mode and radiate in the stem, which is similar to that in the linear case. On the other hand, the light beam injected into the thicker branch will evolve to the symmetric mode for power less than a critical value. This critical value of power is limited by the maximum guide power in the stem.

The characteristics of the above Y junction are useful in the application of the optical network. For example, in a time-multiplexed drop-and-insert network, the signal whose power is above a certain amount can be inserted into the loop easily from the terminals by the nonlinear thinner branch of the Y junction, and the signal that propagates in the loop is not affected regardless of its power. Because the external modulation is not needed, a high-bit-rate operation is expected.

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