Spot size transformer with a periodically segmented waveguide based on InP

F. Dorgeuille, B. Mersali, S. François, G. Hervé-Gruyer, and M. Filoche

France Telecom, CNET, Laboratoire de Bagneux, 196 Avenue Henri-Ravera, B.P. 107, F-92225 Bagneux Cedex, France

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We report what is to our knowledge the first optimization of a spot size transformer by use of a periodically segmented waveguide for photonic integrated circuits based on InP. It is shown that a nonlinear variation of the segmentation ratio along the propagation direction allows one to make an adiabatic transition of a short length. A simple method based on the study of a beveled edge transition is presented for the optimization of such a device. Internal losses in the transition region as low as 1.2 dB are obtained between a coupling waveguide and a simple heterostructure waveguide, with a very high transition spot size expansion factor.

For photonic integrated circuits (PIC's) based on InP, the use of a spot size transformer and a coupling waveguide is necessary to solve the problems set by fiber-chip coupling losses and misalignment during the packaging. Waveguides used to make PIC's present very tight and elliptical spot sizes. On the contrary, the spot size of a single-mode fiber is large and circular. Coupling waveguides, particularly diluted quantum-well waveguides, are designed such that their spot size is similar to the fiber one, resulting in lower coupling losses.[1] A spot size transformer is a device that permits the adiabatic transformation of the integrated-optical circuit spot size into the coupling waveguide spot size.[2] An original method of making the modal adaptation consists of using a periodically segmented waveguide (PSW) with a variable segmentation ratio along the propagation direction.[3] Properties of PSW's have already been theoretically investigated[4,5] and characterized[6] for $LiNbO_3$ material devices.

We deal here with the case of a structure in which the optical circuit is based on a single-heterostructure (SH) waveguide, under which lies a coupling waveguide with diluted quantum wells[7] (Fig. 1). If the diluted quantum wells are grown in the first epitaxy, the processing would remain very simple, but at the expense of misalignment losses. The spot size diameters at the $1/e^2$ values of the light intensity are 10.7 μm × 6.3 μm and 3.5 μm × 0.8 μm for the coupling and the circuit waveguide, respectively. Coupling losses that are represented by the overlap integral between the two modes reflect the misalignment and difference of shape and are computed at 28 dB.[8] These losses arise mostly from the vertical distribution of the fields in the overlap integral. Comparatively, losses coming from the lateral distribution of the fields are very low. Simple methods to make the modal adaptation in this direction have already been demonstrated.[9] Thus, in the following, we are interested only in the optimization of the losses in the vertical plane of the transition (i.e., plane x, z in Fig. 1).

The SH waveguide is made of InGaAsP material ($\lambda_g = 1.3\ \mu$m) with a refractive index $n_Q = 3.38$ at the operating wavelength $\lambda_s = 1.55\ \mu$m. It is segmented to yield adiabatic conversion of the field (Fig. 1). The segmentation period Λ is kept constant along the propagation axis. Γ is the length of the InP material ($n_{\mathrm{InP}} = 3.17$ at $\lambda_s = 1.55\ \mu$m), so that the segmentation ratio Γ/Λ lies in the [0, 1] range. The effective index and the confinement of the mode in a PSW depend only on the segmentation ratio Γ/Λ.[5] The variation of the segmentation ratio within the [0, 1] range along the structure allows one to go progressively from the mode of the SH waveguide ($\Gamma = 0$) to the mode of the diluted quantum-well waveguide ($\Gamma = \Lambda$).

For an adiabatic transition we obtained a linear transformation of the field along the z-propagation axis. The value of the overlap integral between the field in the transition region (for a given z value) and the SH waveguide mode must vary linearly along the transition. This requires the knowledge of the field in perpendicular sections to the z axis. The principle of a PSW is, however, based on an average index guiding. Only a beam-propagation method into three dimensions, taking into account the longitudinal discontinuities, would then be appropriate.[5] But

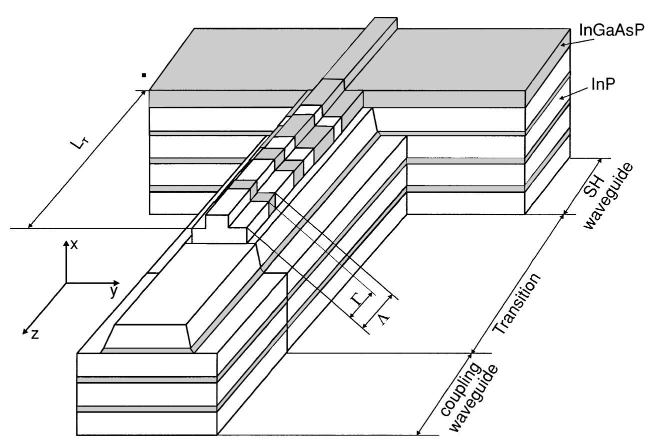

Fig. 1. Adiabatic transition made from a periodically segmented SH waveguide in which the segmented ratio Γ/Λ is variable between a coupling waveguide using diluted quantum wells[7] and a SH waveguide.

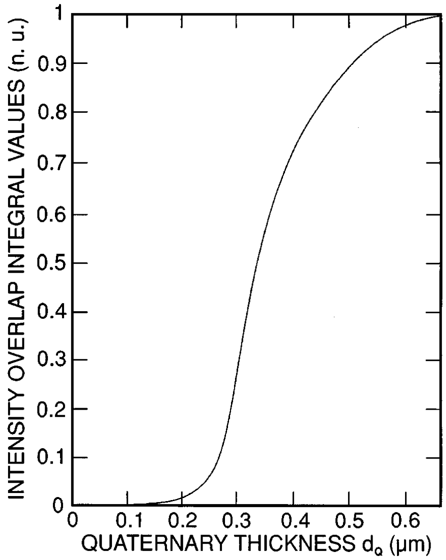

Fig. 2. Optical field overlap figures between the SH waveguide of $d_{\mathrm{SH}} = 0.65\ \mu\mathrm{m}$ and a SH waveguide of d_Q varying from d_{SH} to 0-μm thickness.

this numerical tool, which is difficult to employ, is not flexible enough to optimize such a device. Also, to cancel the problem of the average index guiding in the modeling, we first compute the profile of an adiabatic transition made with a beveled edge. We then deduce from it the evolution of the segmentation ratio along the transition, which is necessary for conservation of the linear transformation of the field.

In the case of a beveled edge transition, the thickness of the guiding layer decreases continuously from the nominal thickness $d_{\mathrm{SH}} = 0.65\ \mu\mathrm{m}$ until it vanishes (diluted quantum-well waveguide). We compute the overlap between the mode in the SH waveguide of thickness d_{SH}, which is taken as a reference, and the mode in a section of thickness d_Q ranging from 0 to d_{SH} (Fig. 2). This yields the beveled edge profile, which permits the linear transformation of the guided mode (Fig. 3, curve a). It can be seen that this profile is strongly nonlinear.

The evolution of the segmentation ratio Γ/Λ for the PSW is deduced from the variation of the thickness d_Q along the beveled edge profile by use of the following relations:

$$V = \frac{2\pi}{\lambda_S} d_{\mathrm{SH}} \sqrt{n_{\mathrm{GSP}}^2 - n_{\mathrm{InP}}^2} = \frac{2\pi}{\lambda_S} d_Q \sqrt{n_Q^2 - n_{\mathrm{InP}}^2}\,, \tag{1}$$

$$n_{\mathrm{GSP}} = n_Q\left(1 - \frac{\Gamma}{\Lambda}\right) + n_{\mathrm{InP}} \frac{\Gamma}{\Lambda}\,, \tag{2}$$

where n_{GSP} is the index-weighted average of the two InGaAsP and InP materials on a period Λ of the PSW.[4,5] Equation (1) expresses the identity between the normalized frequencies V of two planar waveguides of length Λ. The guiding layer of the first plane has an average refractive index, n_{GSP}, that varies along the transition. Its thickness is constant ($d_{\mathrm{SH}} = 0.65\ \mu\mathrm{m}$). The second plane has a d_Q thickness that varies, whereas the refractive index n_Q remains constant. Equation (2) permits computation of n_{GSP} in accordance with the segmentation ratio Γ/Λ. Thus both equations permit the function $\Gamma/\Lambda = f(z)$ to be found for which we obtain an adiabatic transition with the PSW (Fig. 3, curve b).

This method does not give any information on the length for which the transition becomes adiabatic. This parameter is determined by considering the light propagation in the beveled edge transition. The internal losses have been estimated for several transition lengths (Fig. 4). A lower-limit length L_C of approximately 150 μm, for which the light is not transmitted, is clearly seen.

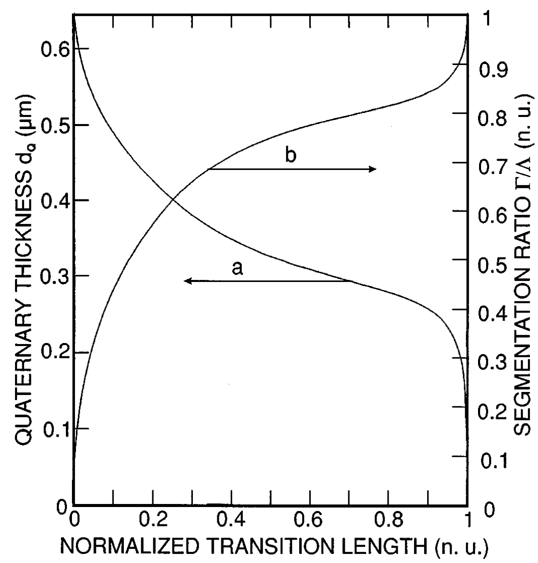

Fig. 3. Curve a: Profile of the vertical tapered transition for which the transformation of the guiding mode along the propagation axis z is linear. Curve b: Function $\Gamma/\Lambda = f(z)$, which conserves the linear transformation of the mode in the propagation direction z given by curve a.

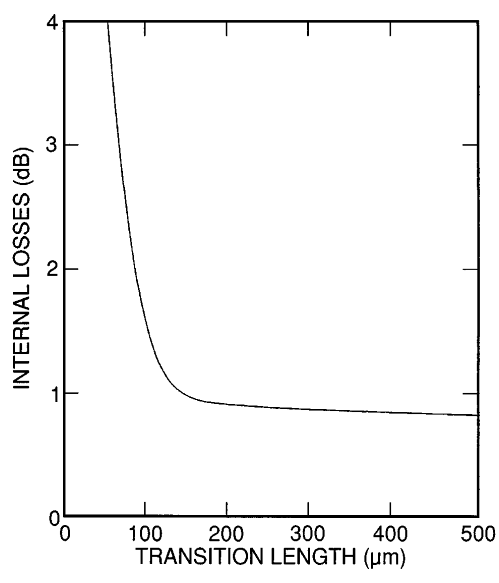

Fig. 4. Internal losses versus the transition length in the case of the computed nonlinear tapering function. For length values >150 μm, the transition features adiabatic behavior.

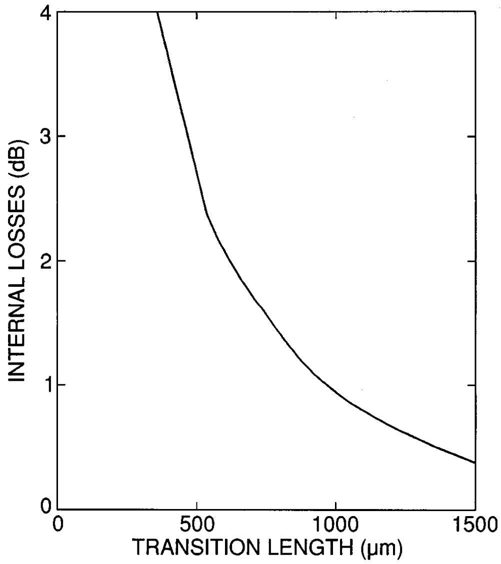

Fig. 5. Internal losses versus the transition length in the case of a linear tapering function.

In the case of the beveled edge-type transition, the propagation simulation using two-dimensional beam-propagation method[8] yields 1 dB of internal losses. The propagation in the PSW, for which the function $\Gamma/\Lambda = f(z)$ was previously detailed (Fig. 3, curve b), yields 1.2 dB of internal losses. The beam-propagation method used is unidirectional but takes into account the InP/InGaAsP interfaces through the calculation of a transmitted coefficient. This approximation is possible because the reflection at the interfaces is very low ($<0.1\%$). In the two cases the transition length is $L_T = 500$ μm. $N_\Lambda = 100$ is the minimum number of periods Λ necessary to produce internal losses comparable with those for the beveled edge case.

We note here that this type of transition does not depend on the operating wavelength λ_s. This confirms that the effect used here is not a grating type, as long as the value of N_Λ is not too low.

Such a low transition length value cannot be reached with a linear variation of the tapering function. Figure 5 shows the internal losses obtained by a linear tapering function. This one yields 1 dB of internal losses for an $L_T = 900$ μm transition length. For the $L_T = 500$ μm value the losses are 2.5 dB. In this case the light is not transmitted by the device for the critical length $L_C = 150$ μm previously determined.

We have proposed to use a PSW to make a spot size transformer for PIC's based on InP. To define the evolution of the segmentation ratio along the propagation direction z, we have developed a simple computing method based on the optimization of the nonlinear shape of a beveled edge–type spot size transformer. In the case of the featured structure, we have shown that the transition internal losses for a transition length of $L_T = 500$ μm could be as low as 1.2 dB for a spot size expansion factor of 7.9 in the vertical plane.

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