A Polarization Independent Optical Directional Coupler Based on Slot Waveguides

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A polarization independent optical directional coupler based on slot waveguides is proposed and analyzed by using rigorous full-vectorial analysis methods based on finite-element scheme. By properly choosing materials and structural parameters, coupling length for quasi-TE modes becomes equal to that for quasi-TM modes. Tolerances to operating wavelength and structural parameters are also discussed. The proposed coupler can be used for highly integrated optical circuits without polarization diversity schemes.

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Recent advances in silicon technology enable us to fabricate ultrasmall optical waveguides and optical functional devices. Especially, optical waveguides based on silicon (Si) and silica (SiO_2) material systems, so called Si-wire waveguides, have been attracted considerable attentions because of their ultrasmall size, strong interaction between light and materials, and so on[1]. Therefore, Si-wire waveguides are promising candidates for future integrated photonics. However, Si-wire waveguide systems are usually highly polarization dependent because of high refractive index contrast between Si ($\approx$ 3.5) and SiO_2 ($\approx$ 1.45). Especially, for optical device applications, polarization dependency is almost unavoidable even if the waveguide itself is polarization independent. For example, optical directional couplers intrinsically have

polarization dependency because multiple waveguides are arranged. Such polarization dependencies in optical devices force us to use, for example, polarization diversity schemes in which polarization beam splitters and polarization rotators are used to align polarization state of lightwave[2,3]. Since these additional components make the total size and structure of the device larger and complex, polarization independent components are highly desired.

In this paper, a polarization independent optical directional coupler based on slot waveguides[4-7] is proposed and analyzed by using rigorous full-vectorial analysis methods based on finite-element scheme[8,9]. By properly choosing materials and structural parameters, coupling length of the coupler for quasi-TE modes (dominant electric fields are polarized to *x* direction) becomes equal to that for quasi-TM modes (dominant electric fields are polarized to *y* direction). The polarization independent operation is confirmed by beam propagation analysis. Tolerances to operating wavelength and structural parameters are also discussed.

Slot waveguides were originally proposed as waveguides in which light is confined in the low refractive index material surrounded by high refractive index materials. In the slot waveguide, low refractive index material (slot region) is sandwiched by high refractive index materials as shown in Fig. 1. In such waveguide geometry, the guided mode polarized to one of the major axis (in this paper, *x*: quasi-TE modes) is strongly confined in the low-index slot region[4,5] because of the electric field discontinuity between high refractive index and low refractive index materials, and light can be strongly confined in the low-index slot region by total internal reflection. Since these guided modes are true guided modes (not leaky modes as in the photonic crystal waveguides), there are no confinement losses. Some optical devices such as ring resonators based on slot waveguides were proposed as novel ultrasmall devices for future integrated photonics[5-7]. Although it was not mentioned in previous literatures, of course, there

exist guided modes for another major axis (y). These guided modes (quasi-TM modes) have very different properties compared with quasi-TE modes. By using these differences, it is possible to realize polarization independent optical directional couplers.

Here, we consider a slot waveguide coupler as shown in Fig. 1. Waveguide parameters for the isolated slot waveguide are as follows: the refractive index of high index region and cladding are, respectively, taken as n_H = 3.48 (Si) and n_C = 1.46 (SiO_2), the waveguide height h = 250 nm, and w_H = 200 nm. w_S is the width of slot region and n_S is the refractive index of slot region. The distance between two cores is d and the operating wavelength is assumed to be 1.55 μm. Solid and dashed lines in Fig. 2 (a) show the coupling length L_c of the directional coupler based on slot waveguides with w_S = 100 nm for d = 1.0 μm and d = 1.5 μm, respectively, as a function of n_S obtained by using full-vector finite-element method (FEM)[8]. We can see that the coupling length for quasi-TE modes is very sensitive to n_S while the coupling length for quasi-TM modes is not so changed. This is because that for quasi-TE modes, the electric field is strongly confined in the slot region as shown in Fig. 2(b), and thus, the coupling length for quasi-TE modes is strongly influenced by the value of n_S. On the other hand, the coupling length for quasi-TM modes is not so affected by the value of n_S because the electric field is distributed in entire core region as shown in Fig. 2 (c). As a result, there is a crossing point in the L_c curves as shown in Fig. 2, at which coupling lengths for quasi-TE and TM modes are identical. The values of L_c and n_S to achieve polarization independent operation are 22.23 μm and n_S = 1.30655 for d = 1.0 μm and 203 μm and n_S = 1.41545 for d = 1.5 μm. Therefore, conditions for achieving polarization independent operation can be tuned by structural parameters. Also, coupling length L_c can be very small for smaller value of d (tens of micrometer for d = 1.0 μm) showing the possibility of realizing ultrasmall polarization independent components. If n_S is 3.48 (simple Si-wire

waveguide coupler), coupling lengths for quasi-TE and TM modes are 45 mm and 1.3 mm, respectively, for d = 1.5 μm resulting in huge polarization dependency. Fig. 3 shows structural parameter conditions to achieve polarization independent operation in slot waveguide couplers. We can see that for larger values of d, larger values of n_S are required for polarization independent operation. Also, for larger values of w_S, larger values of n_S and d are required for polarization independent operation. From this figure, structural parameters to achieve polarization independent operation can be determined for the materials embedded in the slot region. For example, if one wants to use only Si and SiO_2 ($n_S = n_C = 1.46$), w_S = 150 nm and d = 1.334 μm are the conditions for the polarization independent coupler. We also performed beam propagation simulation[9] of the coupler and confirmed that coupling lengths for both polarized modes are the same resulting in polarization independent operation.

It is important to know how much the tolerance to various waveguide parameters is because in usual, these nanometer sized optical devices are very sensitive to waveguide parameters. Fig. 4 shows the crosstalk of polarization independent slot waveguide coupler with w_S = 100 nm, n_S = 1.41545, and d = 1.5 μm, as a function of wavelength at the propagation distance of 203 μm (coupling length at the wavelength of 1.55 μm). Here, the crosstalk is defined as

$$10\log\frac{P_1}{P_2} \tag{1}$$

where P_1 and P_2 are the optical powers in the input and the output ports, respectively. From this figure, the bandwidth in which the crosstalk is lower than 20 dB is 17 nm for quasi-TE modes and 13 nm for quasi-TM modes. In slot waveguides, because light confinement mechanism is total internal reflection, wavelength dependence is not so strong[4,5] compared with other candidates for ultrasmall optical waveguides such as photonic crystal waveguides[10] in which light confinement is depend on interference effects and thus, strong waveguide dispersion can

not be avoided. Fig. 5 shows the relative coupling length of slot waveguide couplers as a function of Δw_H. Here, the structural parameters for the coupler are the same as in the case of Fig. 5 and the operating wavelength is 1.55 μm. Δw_H is the deviation from the original value of w_H = 200 nm and $L_{c,org}$ is the coupling length when $\Delta w_H = 0$. We can see that the influence for the coupling length of quasi-TE modes is stronger than that of quasi-TM modes. Judging from the results of Fig. 5, the tolerance to w_H is not so strong, however, it also implies that the dramatic change of propagation characteristics can be easily obtained with a little perturbation induced by external effects, for example, thermo-optic effects and nonlinear optical effects, showing the possibility of realizing ultrasmall optical functional devices with a low operating power.

In conclusion, we have proposed a polarization independent optical directional coupler based on slot waveguides. The polarization independent operation was confirmed by full-vectorial modal and beam propagation analyses based on finite-element scheme. Tolerances to operating wavelength and structural parameters were also discussed. Proposed couplers can be used not only for ultrasmall polarization independent couplers but also for ultrasmall tunable functional optical devices.

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List of Figure Captions

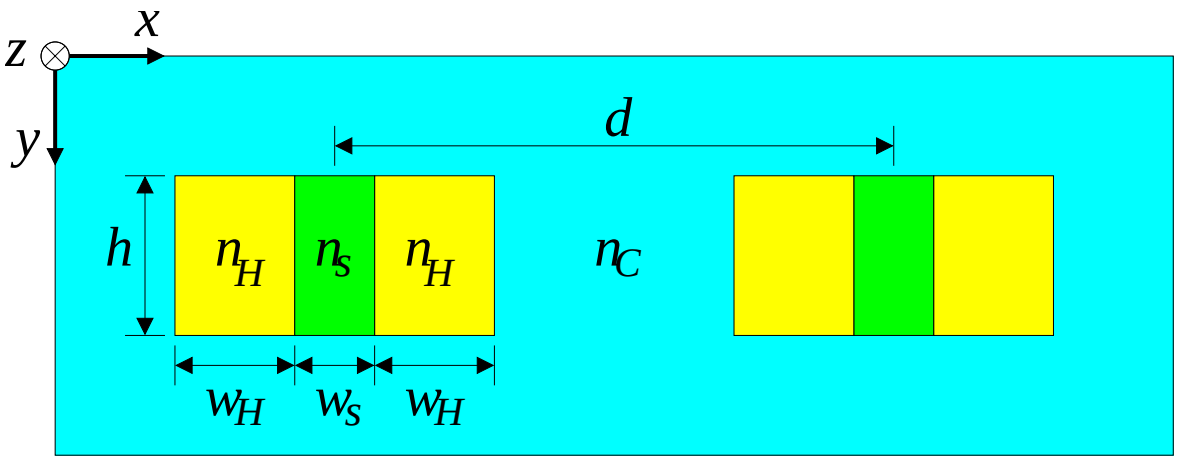
Fig. 1. A slot waveguide coupler.

Fig. 2. (a) Coupling lengths of the slot waveguide couplers as a function of n_s for d = 1.0 μm and d = 1.5 μm. (b) and (c) Dominant electric field distributions of quasi-TE and TM modes, respectively.

Fig. 3. Structural parameter conditions to achieve polarization independent operation in slot waveguide couplers.

Fig. 4 Crosstalk of slot waveguide coupler as a function of wavelength.

Fig. 5 Coupling lengths of slot waveguide couplers as a function of Δw_H.



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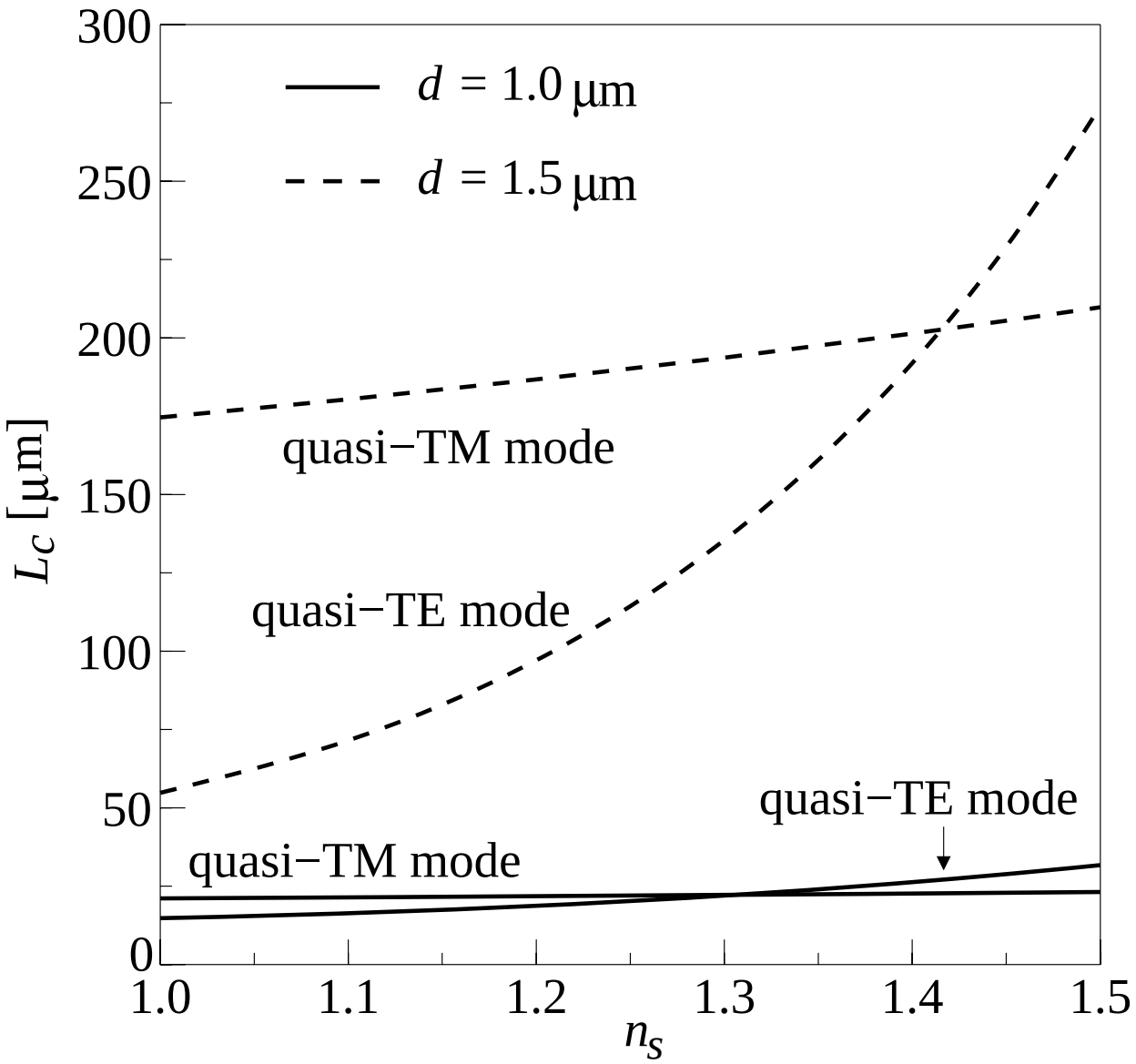
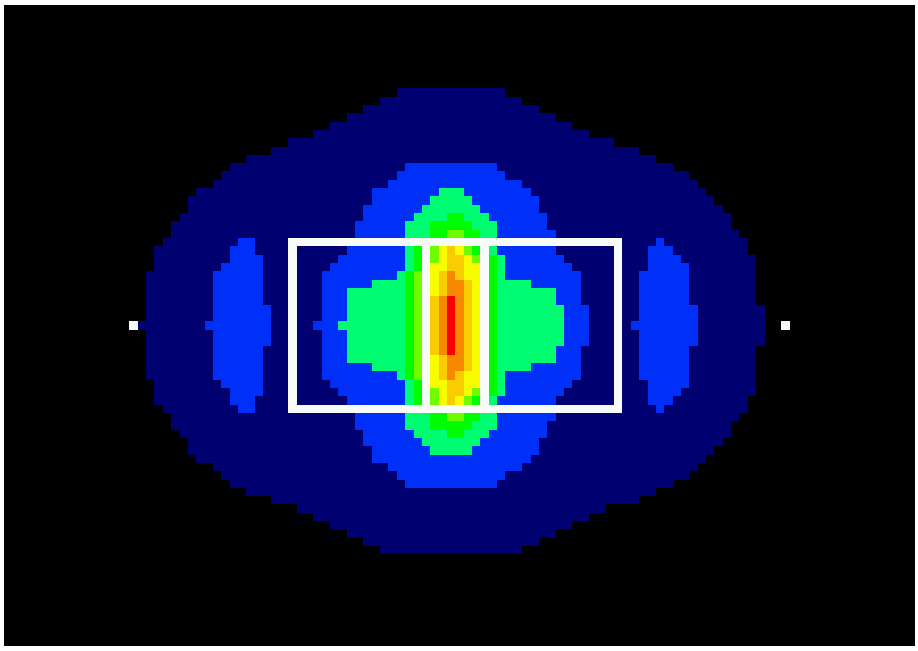
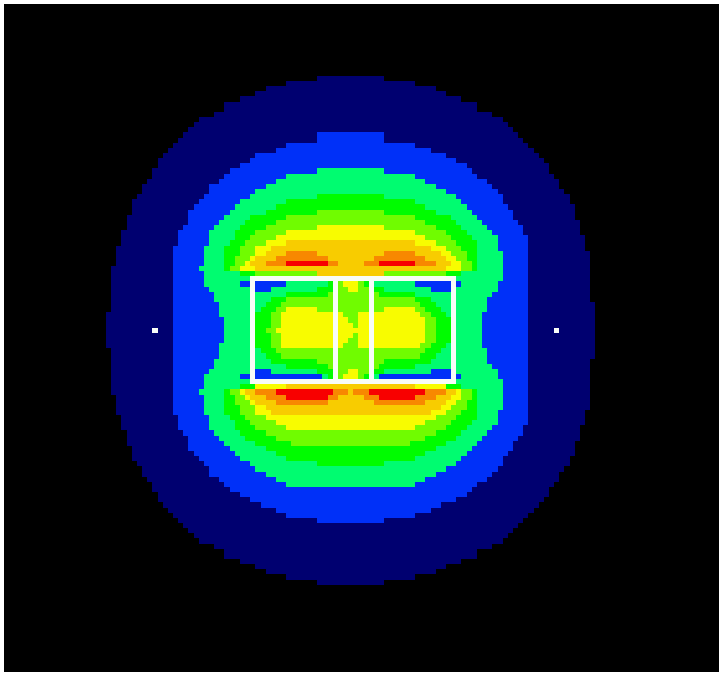

300
250
200
150
100
50
0
L_C [μm]
d = 1.0 μm
d = 1.5 μm
quasi−TM mode
quasi−TE mode
quasi−TE mode
quasi−TM mode
1.0
1.1
1.2
1.3
1.4
1.5
n_s

(a)

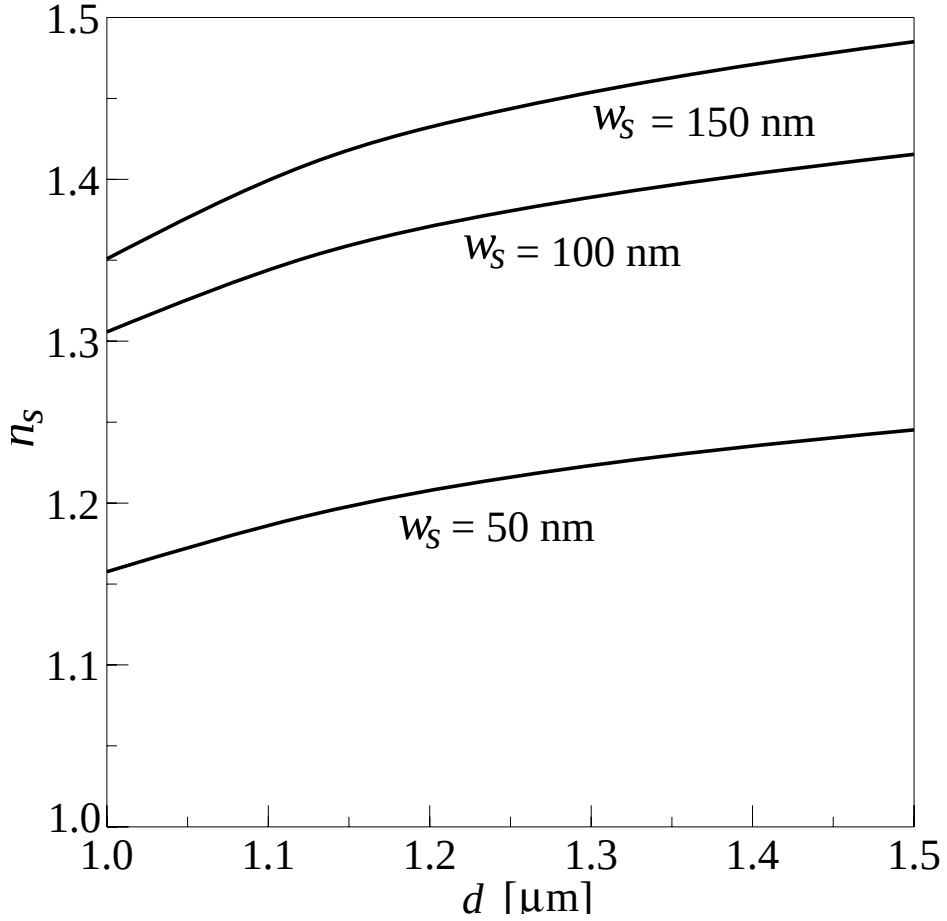


(b)



(c)

Fig. 2 (a) Coupling lengths of the slot waveguide couplers as a function of n_s for d = 1.0 μm and d = 1.5 μm. (b) and (c) Dominant electric field distributions of quasi-TE and TM modes, respectively.



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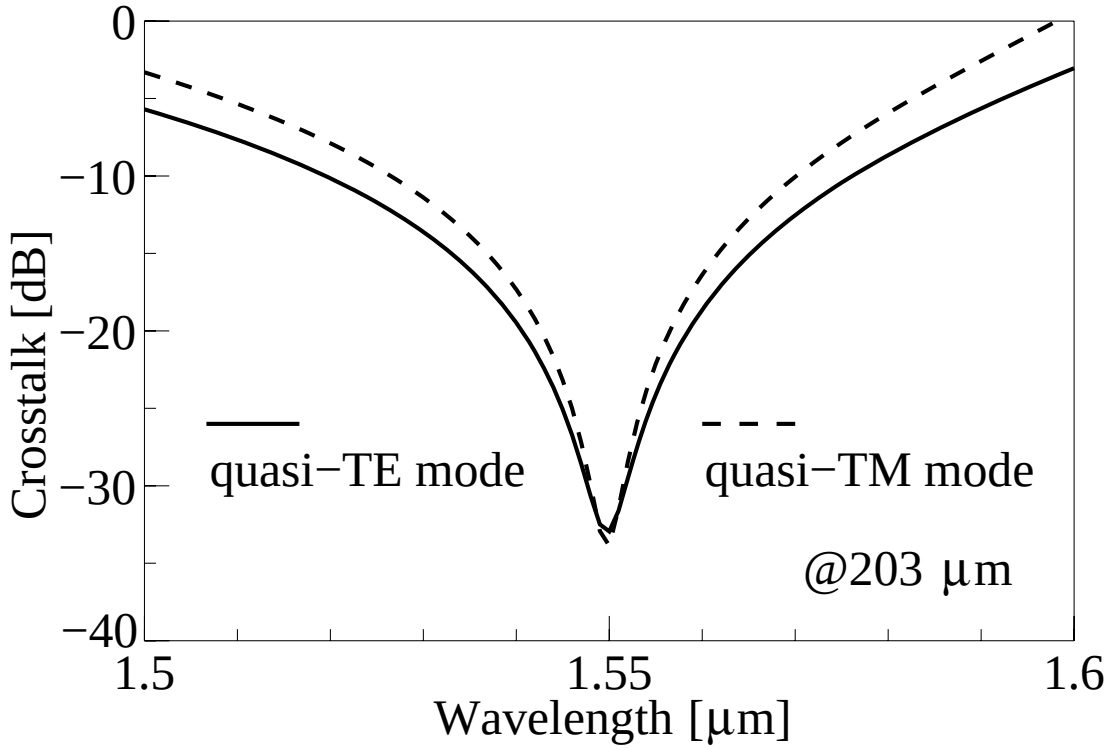

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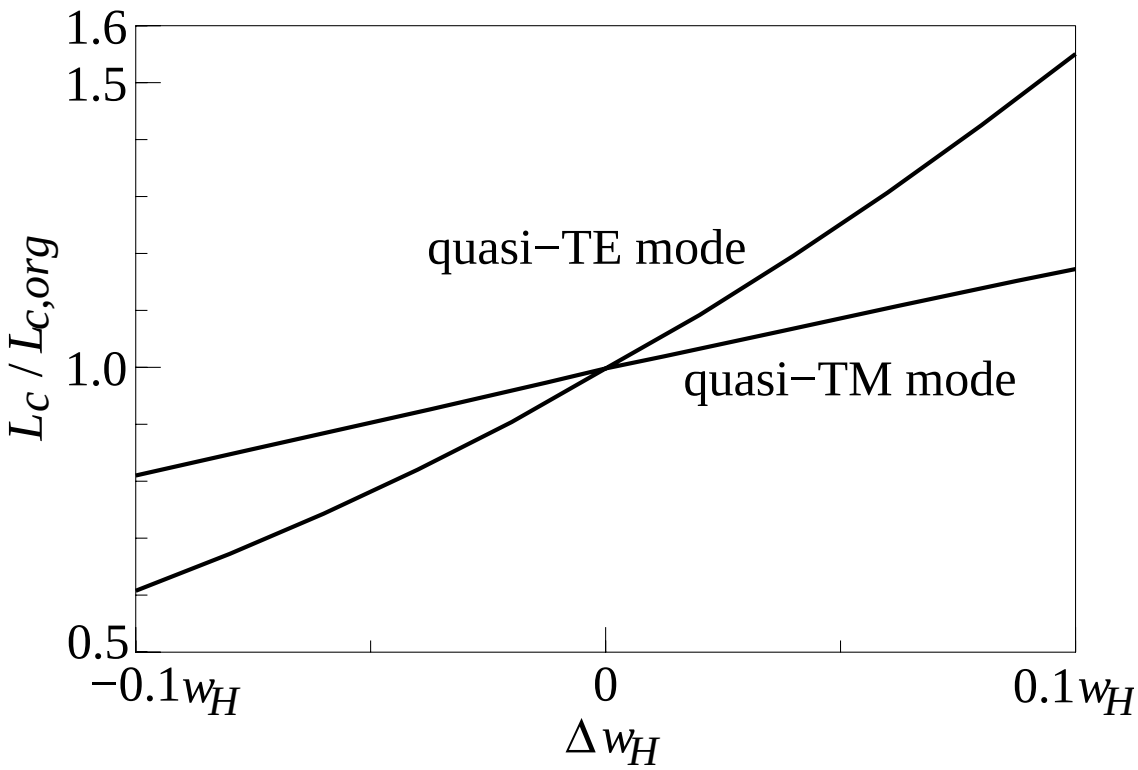

Fig. 5 Coupling lengths of slot waveguide couplers as a function of Δw_H.