TE-TM coupling of a standard fiber to a Si-wire waveguide

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Abstract: *Light coupling form a standard small core fiber to a Si-wire waveguide is demonstrated for both TE and TM through a vertical coupler. Exhaustive design criteria are presented and experimentally validated. A polarization independent couping is realized as a first trial with an efficiency of 72%.*

Introduction

The Si-wire waveguides realized from a silicon on insulator (SOI) wafer are a promising technological platform for a number of applications in both the communication and the optoelectronic word [1].

Due to the very high index contrast $\Delta n=2$, these tiny waveguides present a very small cross section, of fractions of communications wavelengths, and the effective area of the fundamental mode is as small as a few tenths of micron. This guarantees a miniaturization of the optical circuits, with a bending radius which can be reduced down to few microns, but on the other side this give rise to the detrimental effect of the scattering losses at the sidewalls. Moreover, coupling light to and from the Si-wire waveguides is still an unsettled technological issue which can limit the potentially widespread application of this platform. Contributions to so high coupling losses arise from the mode-size and the effective index mismatch.

Many different approaches have been attempted to solve this problem, blazing a trail, still strongly dependent on a challenging technological quality.

By an inverse nanotaper directly made on the silicon waveguide coupling losses of a few dB can be achieved with lensed fibers, for both the polarizations [2]. Nevertheless these fibers are not reliable for commercial applications. Coupling from a standard fiber has been demonstrated by vertical grating couplers, and the maximum coupling efficiency yet demonstrated is 69% for a single polarization [3]. The most simple and reliable approach on the technological side is the vertical coupling to an intermediate waveguide with low index contrast, having a good mode matching with a fiber. This approach has been demonstrated by different labs for a TE-like polarization coupling [4-6], while a polarization independent coupler still requires a more exhaustive study.

The aim of the present contribution is to demonstrate that an optimum standard fiber-to-Si-wire waveguide coupler can be obtained, optimized for low polarization dependence and low losses, through an exahustive review of the design procedure focousing on the main constraints with the aim of relaxing the technological issues. An experimental study of a preliminary structure is presented as a validation.

Design criteria

The mode adapter consists in a vertical coupler between a Si-wire tapered waveguide and a low index contrast waveguide which can be efficiently coupled to a standard optical fiber, as shown in Fig.1.

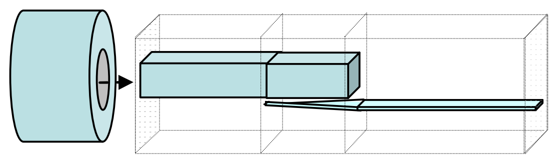

Fig. 1 The fiber to Si-wire coupling through an intermediate waveguide vertically coupled by means of a silicon taper.

The coupling between the lower and the upper waveguide modes requires the phase matching condition to be satisfied in order to obtain a complete power transfer. This is achieved locally by tapering the silicon wire, because the propagation constant scales down with the wire width, as it is shown in Fig.2 by the solid lines, which represent the effective index of the TE-like and the TM-like fundamental modes of the wire. The upper waveguide has a uniform cross section along the coupler and consequently the effective index of the fundamental mode is fixed by the index contrast and is reported on the figure too (dashed line).

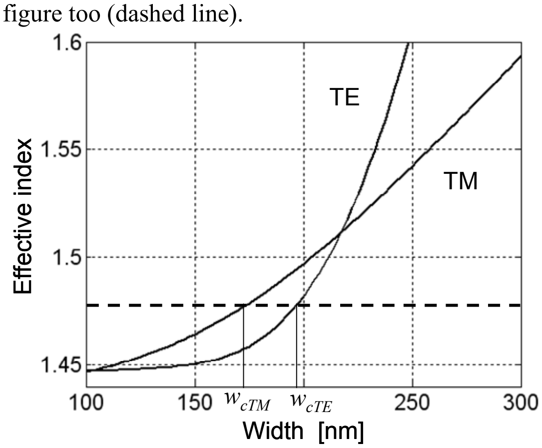

Fig.2 The effective index of the fundamental TE-like and TM-like modes of a Si-wire (solid lines) vs. width. The dotted line is the effective index of the upper waveguide. The phase matching condition between the two waveguides is satisfied in w_c for the two polarization states.

Each dispersion curve crosses the upper waveguide effective index in correspondence of the width w_c of the optimum phase matching condition, in whose surroundings takes place the coupling.

In general, w_c is different for the two polarizations, and depends on the index contrast Δn of the upper waveguide, being large in case of a high Δn, and narrow for a low Δn. The high slope of the effective index of the modes of the Si-wire vs. width, plays an important role in the working principle of the coupler, because it allows the phase matching condition to be fulfilled yust over a very short length along the taper. In fact the taper can be locally modelled over a length dL as a uniform asynchronous coupler with transfer function in the cross condition given by:

$$dP = \frac{\kappa^2}{\delta^2} \sin^2(\delta dL)$$

with $\delta^2 = \kappa^2 + \Delta\beta^2 / 4$, where κ is the coupling coefficient and $\Delta\beta$ is the difference of the propagation constants of the two isolated waveguides and depends on the taper width w and on the gap g [7]. The ratio κ/δ is unitary for $w=w_c$, and is significant only in a small range of widths between w_0 and w_f, which define the maximum range of the coupling and can be less than *50nm* wide, depending on the vertical gap. This is the main origin of the withstanding functioning of this mode adapter, which results to be very tolerant to fabrication errors both on the waveguide dimensions and on the layers displacement, as it will be experimentally demonstrated in the following.

For an optimum design of the mode adapter, a key point is the right choice of the Δn of the upper waveguide, looking for the best compromise among three limiting factors: the minimum reliable taper width, the impact of leakage losses and the optical fiber *MFD*. In particular, the minimum tip width technologically reliable, is ultimately limited by the lithography resolution and it defines the minimum value of the lower boundary. But a more severe restriction is given by the buffer oxide thickness which is tipically limited to a few micrometers if the silicon on insulator (SOI) technology is used for the realization of the Si-wires. As a consequence, both the waveguides have a limited buffer layer which determs leakage losses to the substrate and an inefficient coupling to the optical fiber. Certainly, the minimum oxide thickness required for a limited impact of the leakage decreases by increasing the Δn, but on the other side as this waveguide has to be efficiently coupled to the optical fiber, it is clear that the index contrast should be kept as low as possible. In order to avoid the use of the lensed fibers, a good compromise is the choice of a standard small core fiber, having a mode field diameter $MFD_f \approx 4\mu m$. This fiber can be efficiently coupled to a square waveguide with $\Delta n=4.5\%$, regular-sized to be monomodal, resulting thus the upper boundary for the usefull range of the Δn that guarantees an efficient and technologically reliable coupling to a standard optical fiber. For all these reasons this was our choice of index contrast.

The minimum oxide thickness required below a waveguide in order to minimize the undesired effects of leakage is found to be mainly dependent on the MFD_{wg} of the waveguide resulting in a condition on the buffer thickness t as $t > 1.25\ MFD_{wg}$, while on the fiber side a good fiber-to-waveguide coupling requires a minimum thickness $t > 0.75\ MFD_f$ [8].

For a waveguide with $\Delta n=4.5\%$, the mode diameter is $MFD_{wg} = 2.6\mu m$, and as a consequence the oxide thickness should be $t \geq 3.5\mu m$.

Once the fiber and the index contrast of the upper waveguide are chosen, there is still a fundamental parameter to be determed, that is the vertical gap between the two waveguides (g). As the strength of the coupler depends on the gap thickness, the minimum working with of the Si-taper (w_0) is consequently influenced by the gap, as it is shown in Fig.4: narrow gaps require very small tips with strong technological requirements [9]. For a minimum tip of $w_0=100nm$, a minimum gap $g=0.6\mu m$ is necessary.

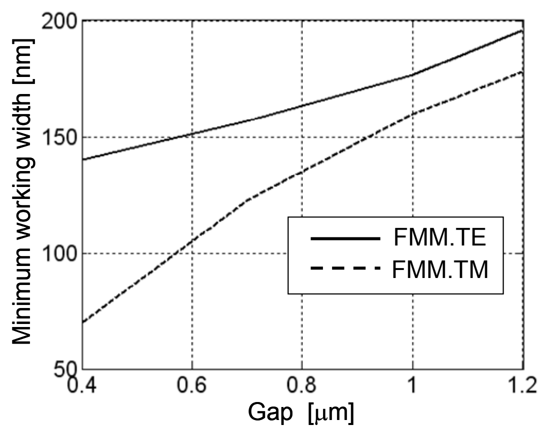

Fig. 4: Minimum working taper with w_0 vs. gap obtained numerically by FMM [10]. The index contrast of the upper waveguide is $\Delta n=4.5\%$.

On the other hand, by increasing the vertical gap, the length of the taper is increased exponentially, as it is shown in Fig.5 for a linear tapering profile. The gap is thus taken as a compromise of minimum reliable tip and device length: a short taper is desirable to limit both the dimension and the losses of the coupler.

The propagation losses in the silicon tip are in fact quite high due to the sidewalls roughness, in particular for the TE-like polarization, wich presents a higher level of losses and also a strong dependence on the wire width.

The taper losses (A_t) are the integral contribution of the wire losses $\alpha(w)$ over the operating range of widths (w_0-w_f) and in case of a linear tapering function it can be written as:

$$A_t = L_t \frac{1}{w_f - w_0} \int_{w_0}^{w_f} \alpha(w) dw = L_t a \qquad (1)$$

being L_t the taper length. The constant a is in general different for the TE and the TM polarization, as so are the wire losses $\alpha(w)$.

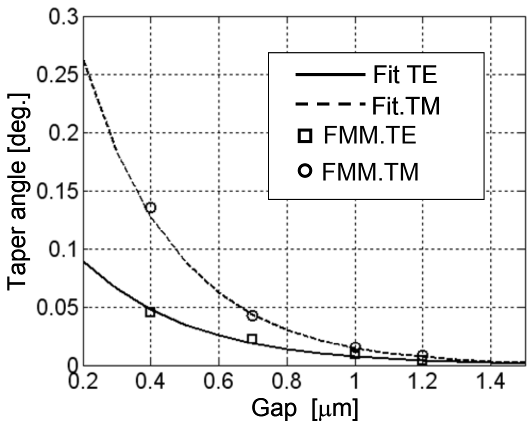

Fig. 5: Si-taper angle vs. gap, calculated by FMM for both the TE-like and the TM-like polarizations.

Experimental results

A set of mode adapters with a linear tapering profile and different lenghts was realized. The upper waveguide has a square-shaped core with $\Delta n=4.5\%$, while the Si-wire core is *220nm* thick and the vertical gap is $g=1.2\mu m$ to ease the integration issues of the two core layers. The minimum taper tip is $w_{tip}=100nm$. The complete structure (Fig.6) consists of an input and an output coupler linked by a Si-wire with $w_N=400nm$, and is realized from a commercial SOI wafer with buffer oxide thickness $t=3\mu m$.

For a best knowledge of all the single elements of the coupler, a number of test patterns was also realized: a family of straight waveguides having $\Delta n=4.5\%$ and different buffer layer thickness t, for quantifying the leakage contribution and the fiber-coupling efficiency, and a few samples of Si-wires having a range of widths for the measurement of the wire losses.

The low index contrast samples, with buffer layer thickness in the range $t=2\text{-}5\mu m$,were characterized by the cut-back method at the wavelength of *1580 nm.* The measured coupling efficiency to a small core fiber with $MFD=4\mu m$ is $A_c=0.2\ dB$ with no polarization dependence for every sample having $t>3\mu m$. Concerning the waveguide loss, the contribution of the material absorption is *0.12 dB/cm* for both polarizations, while the leakage depends exponentially on the substrate thickness and at the working point of the mode adapter, that is $t=4.4\mu m$, the additional leakage losses are *0.25 dB/cm* for the TM polarization and *0.05 dB/cm* for the TE polarization. In Fig.6 a complete set of results on the leakage loss vs. the thickness t is reported. It has to be observed that for a good performance of the mode adapter only a few millimiters of waveguide are required.

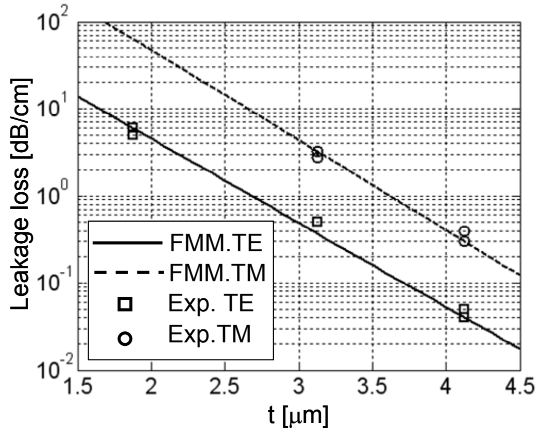

Fig. 6: Leakage loss of the waveguide with Δn=4.5%, versus buffer thickness for both the TE and TM fundamental modes. Solid lines are the numerical results, dots are the experimental ones.

The wire loss $\alpha(w)$ was characterized over a family of Si-wire waveguides with w in the range *150* to *700 nm*. The experimental data are fitted with a partially exponential and partially gaussian model which takes into account of both the leakage and the roughness contribution to the loss:

$$\alpha(w) = A\exp\left(-\frac{w}{B}\right) + C\exp\left(-\frac{(w-D)^2}{E}\right) + F\ .$$

The resulting curves for both the TE-like and the TM-like modes are presented in Fig.7: it is verified that the sidewall roughness mainly affects the TE polarization. The expected propagation loss of a Si taper can be then calculated as in (1) by integrating the experimental curve over the working width range from w_{0TE}=170nm (w_{0TM}=160 nm) to $w_f=w_N=400nm$.

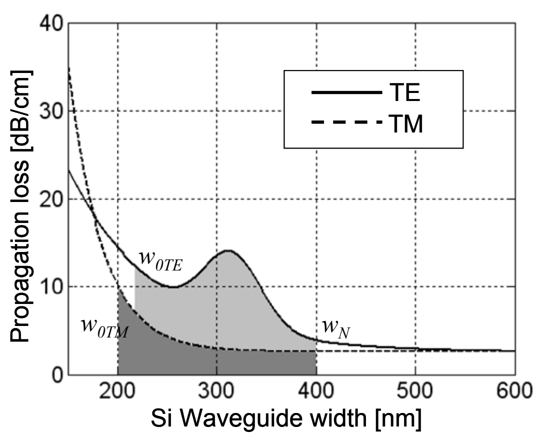

Fig. 7: Propagation loss of a Si waveguide versus waveguide width for both TE and TM polarization states. The grey zone is indicating the widths working range of the coupler.

The resulting loss curves are reported in Fig.8 versus the taper length, and are a reference for the analysis of the experimental results obtained from the characterization of the test structure. The slope of each cur-

ve is the constant *a* calculated as in *(1)* for both the polarizations. As its value is quite different for the TE-like and the TM-like mode it is hard with a linear profile to obtain a polarization independent coupling, unless a very short taper is used.
The experimental points are the loss contribution due to the propagation in the Si taper and also to the vertical coupling efficiency. They are obtained from the insertion loss measurement, by subtracting all the loss contribution given by the fiber to waveguide coupling and by the propagation in the upper waveguide and in the linking wire, previously evaluated.

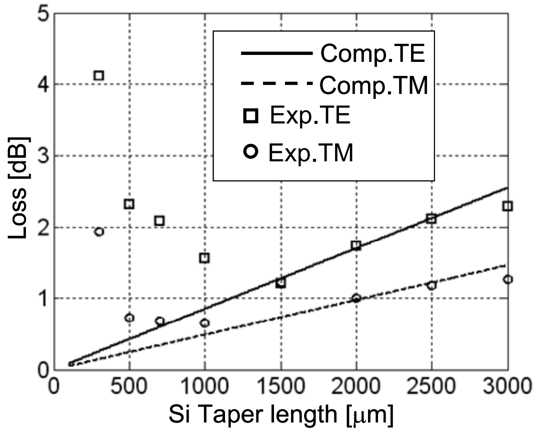

Fig. 8: Computed (solid and dashed line) and measured (squares and dots) losses of the vertical coupling process and the Si linearly tapered waveguide.

If $L_t \geq 1500$ µm the experimental points agree with the straight lines: the taper loss may be high, but the vertical coupling efficiency is close to a unitary value. On the other hand, for $L_t < 1500$ µm the points depart from the calculated lines: the vertical coupling efficiency decreases as L_t is decreased, because the vertical coupler is no longer adiabatic that is the coupling region is too short and the power transfer is not complete. The best result is so far achieved for L_t*=1500µm* representing a good compromise between vertical coupling efficiency and Si taper loss. In this case the measured fiber-to-Si waveguide losses are *1.4* dB for TE and *1.5* for TM.
While the TE loss is completely in accordance to the expected value, the TM loss is about *0.5 dB* higher probably due to experimental tolerances.
A further interesting result is the high tolerance to the layer displacements in case of different taper lengths, which increases with the taper length: for a taper length L_t*=2mm* a displacement of *0.5µm* doesn't affect the coupling, as shown in Fig.9.

Conclusions

A TE and TM coupling from fiber to Si-wire *220x400nm* waveguide has been exhaustively studied and experimentally demonstrated. Design criteria are presented with the aim of relaxing the technological constraints on the fiber side and on the minimum wire width requided. A prototype of the device according to the discussed design criteria has been fabricated by Pirelli Labs Optical Innovation. As a first trial an almost polarization independent coupling efficiency of 72% was demonstrated experimentally.

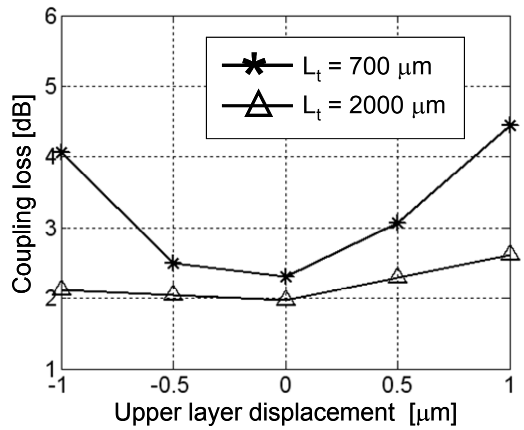

Fig. 9: Eperimental sensitivity of the coupling efficiency to upper layer relative displacement for TE polarization and two taper length L_t.

An optimization of the structure can be obtained either on the technological side by a further reduction of the sidewall roughness of the Si-taper, or on the design side by an opportune choice of the taper prfile or by reducing the vertical gap, in order to reduce the structure length. Further fabrications are in progress.

Acknowledgments

The authors would like to thank the technological staff of Pirelli Labs for the realization of the devices and for the useful technical discussions held with the design group. A special thanks to Dr. M. Artiglia for his useful advice.

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