A Very Short Planar Silica Spot-Size Converter Using a Nonperiodic Segmented Waveguide

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***Abstract*—To reduce the coupling loss of a fiber-to-ridge waveguide connection, a planar silica spot-size converter for a wavelength of 1.55 μm is implemented in the form of a nonperiodic segmented waveguide structure with irregular tapering. A simple single-step lithography process is sufficient for the fabrication of the planar structures. An evolutionary algorithm has been successfully applied for the optimization. The simulated results obtained with a three-dimensional (3-D) finite difference beam propagation method (FD-BPM) program are compared with measurements of implemented couplers, showing very good agreement. A waveguide-to-fiber coupling efficiency improvement exceeding 2 dB per converter is shown. Structures obtained with this approach are very short ($\sim$140 μm) and simple to integrate on the same wafer with other planar structures such as phased arrays or ring resonator structures.**

***Index Terms*— BPM, coupling, gratings, planar waveguides, SiON, spot-size converter.**

I. Introduction

At the interface of integrated optical waveguide structures and fibers, the problem of fiber-to-chip coupling arises.

Planar optical lightwave circuits on silica [1] whose waveguides are matched to single-mode fibers may show negligible loss for butt fiber-to-chip coupling, for example, when using small effective refractive index contrasts [2] or when implementing oversized single-mode waveguides [3], [4]. However, the low refractive-index contrast associated with such designs leads to bent waveguide structures having radii of more than 15 mm. This considerably hinders a further device miniaturization in devices such as phased array waveguide multiplexers or ring resonators. Increasing the index contrast allows us to reduce the bending radius, but at the expense of a reduced butt fiber-to-chip coupling efficiency. By properly designing and integrating spot-size or mode converters, this drawback can be overcome. In particular, it is important that compact spot-size converters can be made because the gain in device miniaturization or even optical integration should not be contradicted by long converters.

Several approaches to spot-size converters have been reported in the literature. Most of them implement combined laterally and vertically tapered waveguide structures. Such structures have been implemented on InP/InGaAsP [5]–[7], InGaAsP [8], InP [9], [10], and InGaAlAs/InAlAs [11], but also on SiO_2/SiON [12]. They are designed to convert the field shape almost perfectly into the fiber mode, but such structures are difficult to integrate and require additional fabrication steps. Another technique uses a tapered fiber to reduce the coupling loss [13]. In industrial applications such structures are not very practical. To integrate the spot-size converters with whole waveguide topology in only one step, planar structures are required. Planar spot-size converters were presented using periodic or quasiperiodic segmented waveguides either with [14], [15] or without [16], [17] lateral tapering. Recently, another type of converter using a grating structure [18] was reported. Such structures transform the mode shape to obtain the fiber mode quite well, but the structures become very long (from several hundred micrometers up to several millimeters).

In this work we present another approach to planar spot-size converters where the structures are very short, using a general nonperiodic segmented waveguide approach with irregular lateral tapering [19]. As the structures are very short, small losses result. Negligible reflections occur due to the nonperiodicity. The converters were designed and implemented in a SiO_2/SiON materials system [20], [21], as used for the fabrication of passive optical add/drop wavelength division multiplexing filters [22]. For this materials system, simple manufacturing procedures are available.

II. Design

The spot-size converter structure was designed using an evolutionary optimization procedure. Such evolutionary algorithms proves to be very efficient especially in the case of demanding combinatorial optimization problems, e.g., when having a large set of discrete parameters. The algorithm itself rely on a collective learning process within a population of potential solutions comparable to the process of natural evolution. It mimics the process of evolution by using genetic reproduction operators such as selection, crossover and mutation. In this optimization scheme, better individuals inherently have higher reproduction probabilities and will therefore survive longer. Because evolutionary algorithms do not necessarily need a well prepared starting point, they are well suited for true synthesis tasks finding novel solutions perhaps not thought to exist.

For the purpose of the evolutionary optimization procedure the structure is divided into a number of segments of equal

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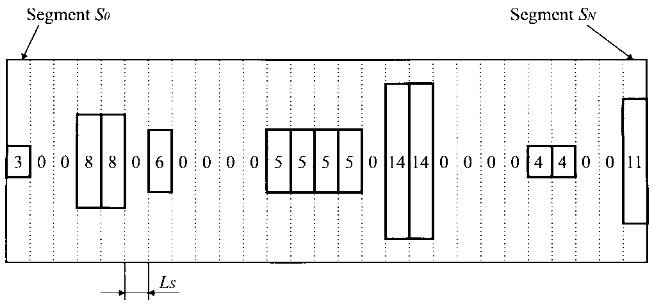

Fig. 1. The representation of the spot-size converters for the optimizer. The converter is divided into segments S_0 to S_N, which can have any discrete value for the width, within given limits. The length of the segments is $L_S = 3$ μm.

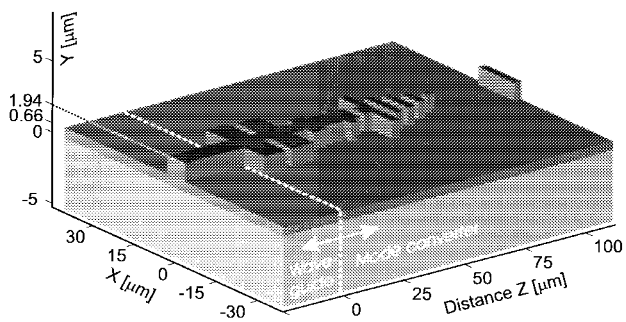

Fig. 2. A possible implementation of the spot-size converter. For visualization purposes the upper cladding is omitted. The lower cladding is at $Y < 0$ (see also Fig. 3 for more details on the waveguide structure). A mode traveling in the $+Z$-direction is widened.

length. Each segment represents a short waveguide with a certain width that is coded by an integer between 0 and 21, where, for example, four means the width of the original waveguide of 3 μm. Therefore a finite number of discrete values, in steps of 0.75 μm, can be created by the optimizer. A segmentation is obtained when the width is zero. Fig. 1 shows this representation for spot-size converters. The representation was chosen such that the total length of the converter that the optimizer may generate is variable [19]. A comprehensive description and analysis of the evolutionary optimization procedure used here has been presented in [23]. A possible resulting converter structure is drawn in Fig. 2.

The initial waveguide structure is a buried ridge waveguide as shown in Fig. 3. The waveguide structure was optimized for small losses and to be single-mode at 1550 nm wavelength. Upper and lower claddings are made of SiO_2 with a refractive index of 1.45, and the core consists of SiON with a refractive index of 1.50. At 1550 nm, this results in a high lateral effective refractive index step of 0.02. When the waveguide is segmented, the residual base layer—with the same refractive index as the central core—remains. That layer considerably hinders a full vertical expansion of the mode.

A evolutionary algorithm was used to optimize the structure. The field simulations were performed with a semivectorial three-dimensional (3-D) finite difference beam propagation method (FD-BPM). The coupling losses were calculated using an overlap-integral between the field at the output of the spot-size converter and the fiber mode, including the radiation

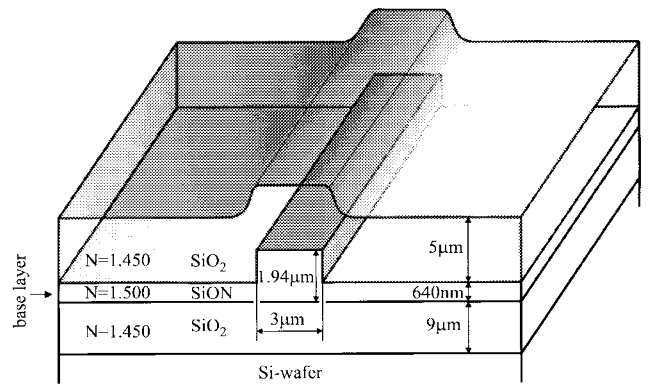

Fig. 3. Schematic representation of the waveguide geometry and refractive indexes at $\lambda = 1550$ nm.

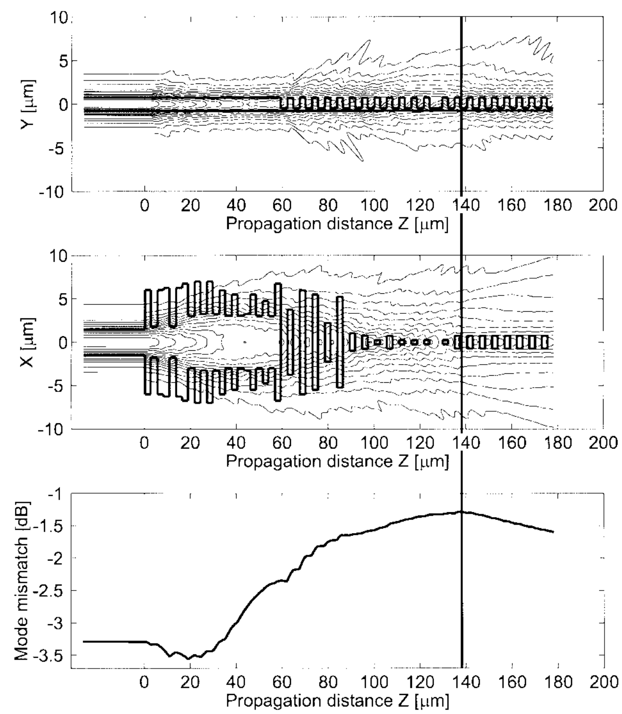

Fig. 4. Structure resulting from the evolutionary algorithm with contour plots of the propagating field (top and center). The converter structure starts at the position 0 μm. The theoretical coupling loss is reduced from 3.3 down to 1.3 dB (bottom). The best conversion is achieved at the distance of 140 μm, marked with a vertical line. Owing to the smooth curve the structure may be cut at any position between 120 and 150 μm without a significant degradation of performance.

losses with an appropriate normalization [19]. The evolutionary algorithm proved to be very efficient in solving such problems. Good results were obtained (less than 1.5 dB loss) after only about 1000 optimization steps. The best result of the optimizer (after 1132 optimization steps) was then optimized with respect to the segment length L_S. An optimum for the coupling losses was found at a segment length L_S of 2.7 μm. The resulting structure is slightly shorter than the original one and therefore has smaller radiation losses. The final structure is shown in Fig. 4, together with the evolution of the coupling efficiency through the converter. A minimal theoretical loss of 1.3 dB can be achieved with this structure. Inspecting the optimized converter structure shown in Fig. 4, two different converter sections may be identified: A first section (between 0 μm and around 60 μm) without segmentation, i.e., only with changes in the waveguide width and a second consecutive section, where true segmentation takes place. Looking now at the actual field pattern within the structure, this classification is additionally underpinned by a different mode treatment considering the two converter sections. The first converter part performs a significant field expansion in the horizontal direction whereas the segmentation in the second part is indispensable for a vertical enlargement of the mode profile. It is worth noting, that this sort of functional partitioning is characteristic for all well performing coupler topologies. The last periodic part of the converter was lengthened to guide the mode further with only small changes in coupling efficiency. This has the advantage that the structure may be cut with a large tolerance of about 30 μm without degrading the performance more than 0.1 dB (Fig. 4).

Reflections are estimated to be very low because of the small difference in the effective refractive index between segmented and nonsegmented waveguides of about 0.02.

The theoretical direct butt-coupling loss was calculated to be 3.3 dB. The performance with a spot-size converter is a coupling loss of 1.3 dB, which results in a coupling improvement of 2 dB as shown in Fig. 4.

III. Implementation

The SiON waveguide structures are deposited by plasma enhanced chemical vapor deposition (PECVD) onto thermally oxidized silicon wafers. Channel waveguides are formed by reactive ion etching. The single mode waveguide design is based on the demand to obtain low-loss bends for radii as small as 1 mm. Small bending radii allow optical components to be designed, e.g., Mach–Zehnder interferometers (MZI's), on a smaller chip size as well as such optical building blocks to be integrated on one chip. To meet this requirement the lateral effective index contrast of the waveguide was chosen to be 0.02, resulting in a width of 3 μm for single-mode operation [20].

To analyze carefully the modeled spot-size converter, straight waveguides of 1.5 cm length were fabricated. Every second waveguide ended with a converter structure. The chip was diced using a wafer saw at the end of the converter and the end facet polished to optical quality.

This permits direct comparison between a spot-size converter and an adjacent conventional butt-coupled straight waveguide, thereby avoiding the influence of fabrication inhomogeneities across the chip.

In the zoomed section of the optical microscope image shown in Fig. 5, it appears that the waveguide segments are rounded due to the lithographic process. This effect can even be advantageous because small, sharp corners are difficult to overgrow conformally in PECVD. Experimentally, we found no negative impact on the performance of the converter. To estimate the influence of geometrical errors different versions of converter designs were implemented, ranging from simple tapered segments to those having sharp or rounded corners. All these variations showed similar results. A theoretical analysis of waveguide roughness and small-scale inhomogeneities [24] shows that such effects have little influence on the eigenmode of the waveguide.

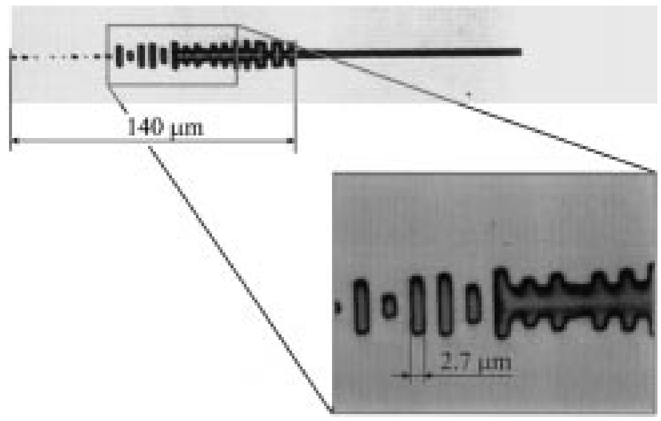

Fig. 5. Optical microscope image of a 140-μm-long spot-size converter structure as developed in photoresist. The rounded corners visible in the zoomed section of the structure are due to the lithographic process. The segment length is 2.7 μm.

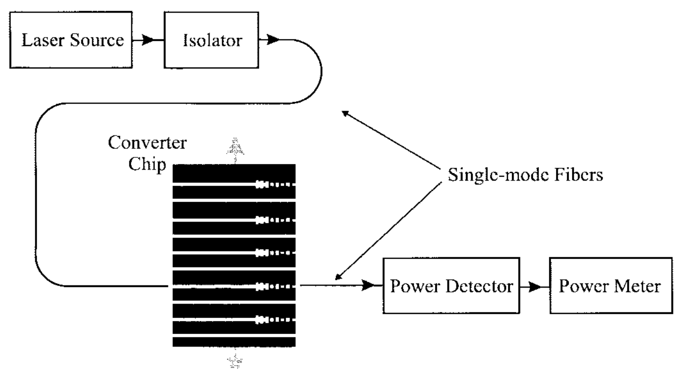

Fig. 6. Schematic image of the measurement setup. The waveguide chip is mounted on a translation stage, which permits us to measure adjacent waveguides rapidly. For reference purposes waveguides with and without coupler are alternately implemented.

IV. Measurements

Fig. 6 shows the measurement setup used. The light emitted from a 1550-nm laser source is guided through an isolator to prevent the light from returning into the laser. With the single-mode fiber, we butt-couple directly into a straight waveguide on the chip. At the other end a converter may be present. After being coupled into a fiber, the light strikes a detector and the signal is measured with a power meter.

The results of the measurements are shown as a comparison between waveguides with and without a spot-size converter. As shown in Fig. 6, converters are placed on only one side of the chip. The improvement of the coupling efficiency is greater than 2 dB per interface (see Fig. 7). Only small variations between consecutive waveguides were measured. The devices have no significant polarization dependence, which was to be expected because of the very small difference in transverse electric (TE) and transverse magnetic (TM) mode shapes

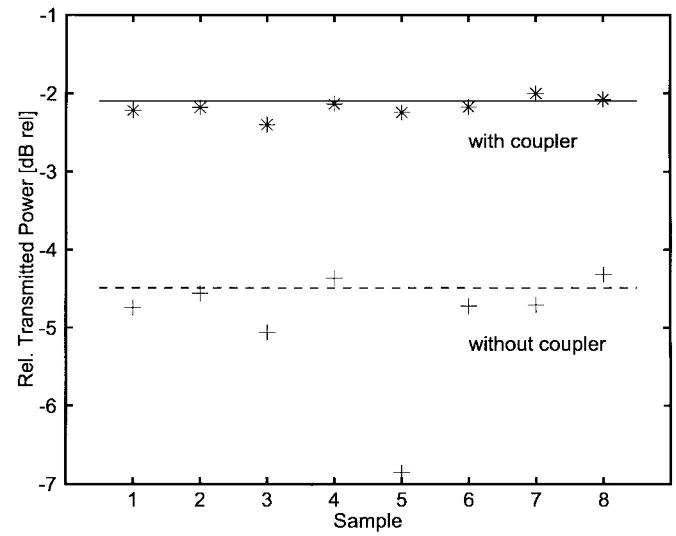

Fig. 7. Comparison between the coupling losses with and without spot-size converter. The improvement with converter is greater than 2 dB per interface, which agrees well with theoretical predictions. The vertical axis shows only a relative difference. No absolute calibration was made.

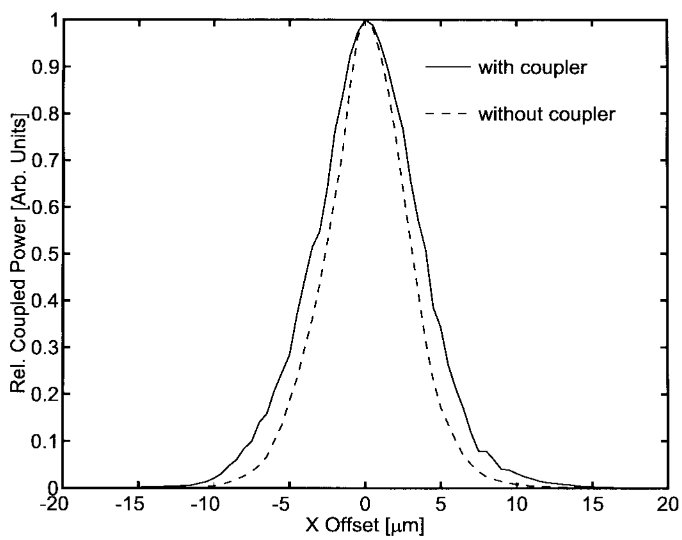

Fig. 8. Measured horizontal fiber alignment sensitivity with and without spot-size converter. Using a converter the horizontal (and also the vertical) alignment is slightly less critical because of the widened field shape. In both cases the fiber is butt-coupled to the chip.

in addition to the small converter length. No measurable difference between TE and TM field expansion was observed. A very low wavelength dependency of less than 0.1 dB from 1.50 to 1.60 μm is expected from simulations.

One important factor is the horizontal and vertical alignment sensitivity when coupling a fiber to the chip. The alignment is slightly less sensitive with the converter (see Fig. 8) as is expected because of the change in the numerical aperture when using a spot-size converter. The coupled power as a function of the gap size between the fiber and the chip shows interference effects in the first 20 μm with only small variations in the order of 5% of the coupling efficiency. The Z-alignment for butt-coupling is less sensitive than for coupling to a lensed fiber.

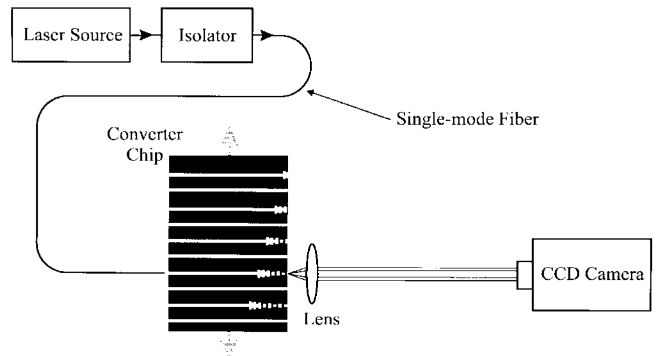

Fig. 9. Setup for near-field measurements. At the output of the converter a lens images the field intensity into a CCD camera. The chip used for this measurement contained converter structures shifted along the waveguide with respect to each other.

A further improvement of the coupling efficiency may be achieved when using an index-matching oil. It was measured to be 0.19 dB (the theoretical value is 0.18 dB) when an index-matching oil of $n = 1.5$ is used. Therefore, when using index-matching oil, the improvement of the coupling efficiency is further increased.

The propagating field intensity is compared to the simulations with near-field measurements. For this purpose a series of identical converters displaced along the waveguide at intervals of several microns are used (see Fig. 9). This allows us to determine the field shape at several positions in the mode converter on a single chip. To measure the near field, a microscope lens was used to image the field intensity into an infrared CCD camera as shown in Fig. 9. All elements are specified for a wavelength of 1.55 μm.

As shown in Fig. 10 the measured near field intensity compares very well with the calculated field profiles through the converter.

The reflections due to the spot-size converter were estimated to be very low. A reflection measurement using a position-sensitive interferometric tool (HP 8504B) with a resolution of 40 μm confirms this estimate. Fig. 11 shows a reflection measurement performed on a double converter structure. The maximum reflection level induced by a converter structure is found to be about -40 dB, which is more than 20 dB smaller than the Fresnel reflection that would occur if a lensed fiber were used to couple to the waveguide. This measurement shows that BPM is an appropriate tool to simulate such structures. Although the reflections are neglected, the transmitted part of the light is correctly simulated.

When taking into account a loss of 0.5 dB/cm of the waveguides, the absolute butt-coupling loss without spot-size converter is 3.7 dB, whereas the coupling loss with spot-size converter is only 1.6 dB, both using index-matching oil. These values compare well with theoretical calculated coupling efficiencies of 3.3 and 1.3 dB, respectively. The main source of discrepancy may come from a residual mode mismatch of the calculated and real waveguide mode with respect to the optical single-mode fiber. Nevertheless the spot-size converter results in an improvement of 2.1 dB per interface.

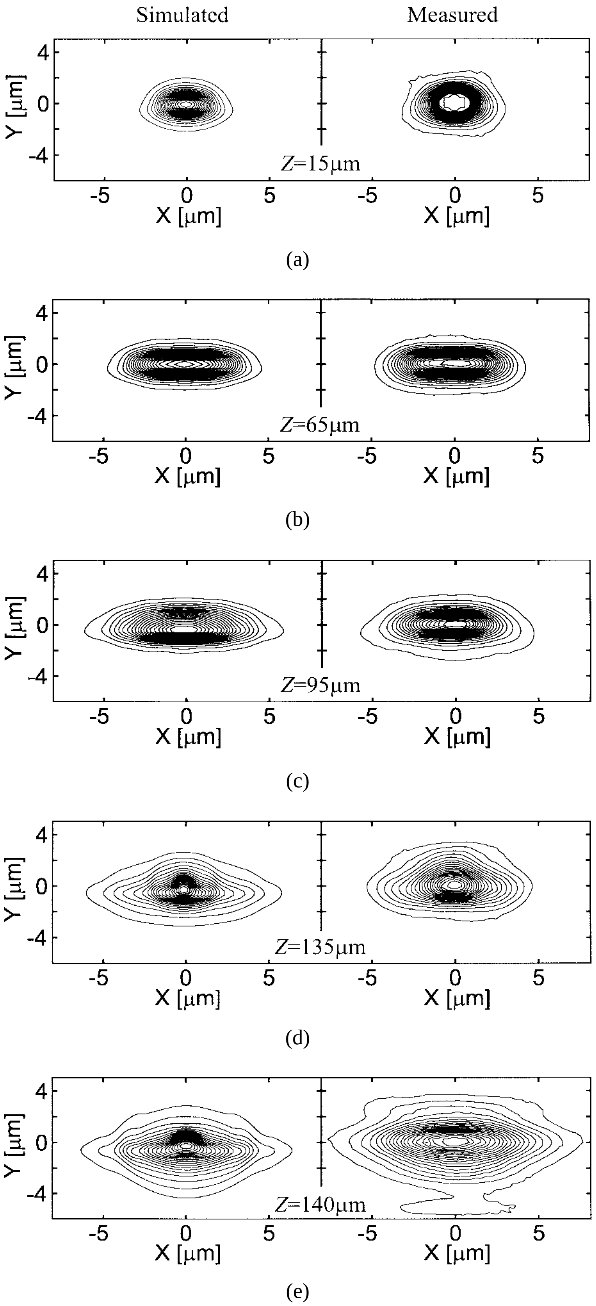

Fig. 10. The calculated intensity distribution (left) is compared with the measured near field (right) through the converter structure. The intensities agree very well with the simulations. The fields are shown for $Z = 15, 65, 95, 135$ μm and at the end of the converter from (a) to (e), respectively.

V. Conclusion

A compact spot-size converter was optimized with an evolutionary algorithm and implemented on high refractive-index contrast SiO_2/SiON material as nonperiodically segmented planar waveguide structure. Planar structures on the chosen material are very cost-effective and may be fabricated using a simple single-step lithography process. The evolutionary optimization results in a converter length of less than 150 μm, which is very short compared to earlier designs. Measured coupling losses and field shapes show very good agreement compared to BPM simulations. A measured improvement

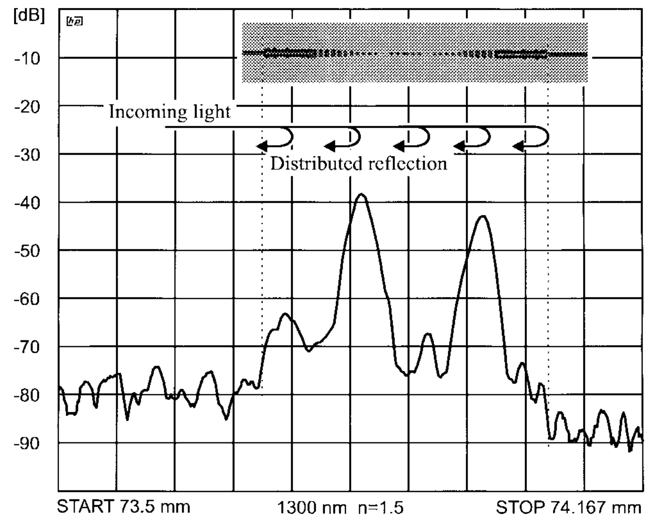

Fig. 11. Reflection measurement on a double converter structure at 1300 nm. This wavelength was used because of the higher precision. The second best optimized structure was used for this measurement. The maximum reflection of one structure is about −40 dB. A picture of the structure is overlaid to show the positions of the reflections. Following the inlet reflection scheme, the slight asymmetry in the reflection signal is caused by an asymmetrical optical excitation of the structure.

of the coupling efficiency of more than 2 dB per interface compared to direct butt coupling was obtained.

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