Design and optimization of optical power splitters for optical access networks

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Abstract
This paper aims to study the design, simulation, and optimization of low-loss Y-branch passive optical splitters up to 64 output ports for telecommunication applications. For a waveguide channel profile, the standard material silica-on-silicon is used. The Y-splitters are designed and simulated at telecommunication operating wavelength, $\lambda = 1550$ nm. Except for the lengths of the used Y-branches, and a core size of the waveguides, design parameters such as port pitch between the waveguides and simulation parameters for all splitters are considered fixed. The simulation results are analyzed to determine the optimum length of the splitters and the optimum core size. Based on this optimization the total length of the highest designed $1 \times 64$ Y-branch splitter was reduced by 41.14 % for a waveguide core ($5 \times 5$) $\mu$m$^2$ compared to the length of splitter with a standard ($6 \times 6$) $\mu$m$^2$ core size.

Keywords Y-branch splitter · Optical properties · Light propagation · Telecommunication

1 Introduction

The Passive Optical Network (PON) is an optical access network infrastructure that uses passive optical components, such as optical fibers, connectors, and optical splitters, to distribute an optical signal. A passive optical splitter divides the incoming optical signal at the input port into two or multiple separate output ports. The same approach can be used in the reverse direction to combine multiple optical signals coupled at the output ports into the input port as well (Kuzyk 1998). Ideally half of the input beam power propagation, i.e., $-3$
dB goes to one of the outputs and the other half to the other output of the splitter (Chróstowski and Hochberg 2016).

One of the most used approaches to split an optical signal is to create it as a cascade of one by two waveguide branches also known as Y-branch optical splitter (Lifante 2003). The Y-branch optical splitters are commonly used in network architectures, as Fiber-To-The-x (FTTx), because of two main advantages: they are polarization and wavelength-independent, i.e., they can be used in the whole telecommunication-operating window. This technology enables high-speed broadband connections simultaneously to multiple users at home (FTTH), building (FTTB), premises (FTTP), or other locations, depending on where the optical fiber is terminated. The main application for PON has been Fiber-to-the-home (FTTH), where the passive optical splitters achieve to share network capacity for a maximum of 128 users (Fröhlich et al. 2015).

The main challenges in the design of Y-branch optical splitters are the asymmetric splitting ratio, (non-uniformity of splitting power), and the large size of the splitter structure. These parameters define the final performance of the Y-branch optical splitters. The principal factors determining the size of the splitters are the used material type and the length of the individual waveguide branches with a corresponding angle.

This paper shows the influence of the waveguide length on the final performance of Y-branch optical splitters and possible optimization. Besides the length optimization, the core size of the waveguide structure is also reduced to avoid the multi-mode propagation of the light. Design and simulation of passive optical components are performed by a commercial photonic software tool OptiBPM from Optiwave, which uses the Beam Propagation Method (BPM) [5].

2 Design and simulation of $1 \times 2^N$ length optimized Y-branch splitters

To design passive optical splitters, low-index-contrast waveguide technology, specifically, silica-on-silicon (SoS) buried rectangular channel waveguide is used. The basic structure of a buried waveguide consists of a longitudinally extended high-index optical medium, called core, which is surrounded in all transverse directions by low-index media, called cladding (Hameed and Obayya 2019). A guided optical wave then propagates in the waveguide along with its longitudinal direction. The refractive-index contrast between the cladding and the core is $\Delta n = 0.75 \%$ with a refractive index of core being $n_c = 1.456$ and refractive index of cladding $n_{cl} = 1.445$. The size of the waveguide was set to $(6 \times 6) \mu m^2$, as this is a standard used waveguide cross-section.

Figure 1a shows the initial design of optimized $1 \times 4$ Y-branch splitter. As can be seen, at the input and output ports, linear waveguides are used and set to have a length of $L(in) = L(out) = 500$ $\mu m$. Port pitch between the output waveguide branches $P(1^{st})$ is set to 127 $\mu m$. This spacing is required for a connection with the fibers (Wang et al. 2014). This initial pitch value is then doubled with every further layer, $L(n)$. Each individual Y-branch is constructed of two waveguides having a predefined arc-cosine shape called “s-bend-arc”. To keep the whole length of the splitters $L$ as short as possible, every Y-branch is individually scanned between selected length ranges, as shown in Fig. 1b. From the graph, it is evident that shorter waveguides feature steeper angle causing higher bending losses. At a particular length $L(n)$, the losses do not decrease anymore and saturate at a particular value. This length is chosen as a final shortest possible Y-branch length for each Y-branch. The optimum length of the particular branches leads
to the optimization of output power, which contributes to high-performance levels of optical devices. Such a cascade arrangement of Y-branches allows the splitting of one input optical signal into four output optical signals. This approach is used for design and optimization of further split ratios $1 \times 8$, $1 \times 16$, $1 \times 32$, and even more complex splitting structures, like $1 \times 64$ Y-branch optical splitters. The results of the Y-branch lengths and simulation performance are shown and described in Serecunova et al. (2020).

Two-dimensional isotropic simulation was performed for every $1 \times 2^N$ Y-branch splitter. For the simulation, the perfectly matched layer (PML) boundary condition is selected. It defines the truncation of the computation domain by layers without any reflection, irrespective of their frequency and angle of incidence [9]. All Y-branch splitters were designed and simulated at telecommunication operating wavelength, $\lambda = 1550$ nm for transverse electric (TE), and transverse magnetic (TM) polarization. The simulation results were almost identical for both polarizations. Anyway, since the TE polarization features lower losses, these simulation results are presented in this paper. Figure 2 shows the design of the highest reached splitting ratio, $1 \times 64$ Y-branch splitter.
3 Core size optimization of Y-branch splitter

The light propagating in the waveguides can propagate in different modes. The number of propagating modes depends on the waveguide dimensions, material, and variation of the refractive indices of both core and cladding. How strongly the optical power is limited to the waveguide core depends on each mode. A mode is characterized by an invariant transversal intensity profile and an effective refractive index $n_{\text{eff}}$. When the effective index is higher than the cladding index, the modes are called guided, or fundamental modes (Selvaraja and Sethi 2018). The fundamental modes normally evince rather small propagation losses. The light beam is limited to the core and intermediate vicinity. Their field distribution decline exponentially in the cladding. The propagation modes that are not restricted to the surrounding core belong to the cladding modes. When the light beam is guided to the center of the core, one may inject some part of the power into cladding modes, if the input light is not well adjusted to the guided mode. Their intensity distribution fills the full cladding region, so they have often large power losses [11].

In the case of $(6 \times 6) \mu m^2$ core size there are two modes: TE0 mode with $n_{\text{eff}} = 1.451$ and TE1 mode with $n_{\text{eff}} = 1.445$, as shown in Fig 3. Zero mode is categorized as a guided mode ($1.451 > 1.445$), and because the first mode has a same refractive index value as a cladding, it is categorized as a cladding mode.

To see the light propagation influence of waveguide core size on the Y-branch splitting ratio the waveguide core size was reduced from $(6 \times 6) \mu m^2$ to $(5.5 \times 5.5) \mu m^2$ and $(5 \times 5) \mu m^2$ to boost only the single-mode light propagation. For core size $(5.5 \times 5.5) \mu m^2$ only one mode with the $n_{\text{eff}} = 1.450$ was calculated and the core size $(5 \times 5) \mu m^2$ has also one mode with $n_{\text{eff}} = 1.449$. Both core sizes belong to the guided mode waveguides because their effective indices of the mode are higher than the cladding index.

The same approach of length optimization, as described in sect. 2, was used for the splitters with the core size of $(5.5 \times 5.5) \mu m^2$ and of $(5 \times 5) \mu m^2$. Every length was scanned in the range again for every particular port pitch to reach the optimal length for Y-branches. The port pitches between the branches remained the same as in the case of Y-branch splitter with a waveguide structure with the $(6 \times 6) \mu m^2$ core size. Table 1 shows the comparison of all Y-branch-lengths for all waveguide core sizes.
Results and discussion

Figure 4 shows the graphical representation of the optical parameters of the highest splitting ratio 1 × 64 Y-branch splitter, i.e., the field distribution achieved at the end of the simulation together with background crosstalk. Background crosstalk calculation ($BX$) does not exist in the standard formula yet. For this calculation, the point of the highest saturation and the highest background crosstalk value is taken into consideration. The final background value is the median transmission value from these values. The maximum background crosstalk does not differ significantly in the case of optical splitters with $(6 \times 6)$ $\mu$m$^2$ and $(5.5 \times 5.5)$ $\mu$m$^2$ waveguide core. As shown in Fig. 4e, with decreasing a core size to $(5 \times 5)$ $\mu$m$^2$, the background value is slightly increased compared to a standard $(6 \times 6)$ $\mu$m$^2$ core size. The fraction of power transferred from the input port to the output port is called insertion loss ($IL$). Insertion loss uniformity $ILu$ (also called non-uniformity) is the difference between the maximum insertion loss and minimum insertion loss of the optical signal in the characteristics. In Figs. 4b, d, and f can be seen that the insertion loss ($IL$) was reduced with the decreasing core size but not that significantly, unlike the non-uniformity that features a considerable improvement.

The splitting parameters and final sizes of the length-optimized and at the same time core size-optimized Y-branch optical splitters with splitting ratio
shows Table 2. For every Y-branch splitter insertion loss, non-uniformity, and background crosstalk are calculated. As can be seen, the length-optimized splitters with the core size $6 \times 6 \, \mu m^2$ feature small footprint as well as outstanding optical performance. Nevertheless, as presented in Table 2, the reduction of the waveguide core size to $(5.5 \times 5.5) \, \mu m^2$ and $(5 \times 5) \, \mu m^2$ leads not only to the significant improvement of the optical properties but also to a much smaller footprint. The optical

Fig. 4 Simulation results of $1 \times 64$ Y-branch splitter for different core sizes, (a) (c) (e) field distribution at the end of simulated structure together with a background crosstalk ($BX$), (b) (d) (f) detailed view of field distribution showing the non-uniformity ($ILu$) and the insertion loss ($IL$)

$1 \times 2, 1 \times 4, 1 \times 8, 1 \times 16, 1 \times 32,$ and $1 \times 64$ shows Table 2. For every Y-branch splitter insertion loss, non-uniformity, and background crosstalk are calculated. As can be seen, the length-optimized splitters with the core size $(6 \times 6) \, \mu m^2$ feature small footprint as well as outstanding optical performance. Nevertheless, as presented in Table 2, the reduction of the waveguide core size to $(5.5 \times 5.5) \, \mu m^2$ and $(5 \times 5) \, \mu m^2$ leads not only to the significant improvement of the optical properties but also to a much smaller footprint. The optical
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Table 2 Comparison of splitting parameters achieved from the simulations of $1 \times 2^N$ Y-branch splitter with waveguide core sizes of $(6 \times 6)$, $(5.5 \times 5.5)$, and $(5 \times 5) \mu m^2$

| Splitter $1 \times 2^N$ | Core size [$\mu m^2$] | ILu [dB] | IL [dB] | BX [dB] | Chip size [$\mu m^2$] |
|------------------------|------------------------|---------|---------|---------|-----------------------|
| $1 \times 2$           | $6 \times 6$           | 0.00    | -3.17   | -43.38  | 3800 $\times$ 127     |
|                        | $5.5 \times 5.5$       | 0.00    | -3.06   | -39.39  | 3600 $\times$ 127     |
|                        | $5 \times 5$           | 0.06    | -3.16   | -35.30  | 3100 $\times$ 127     |
| $1 \times 4$           | $6 \times 6$           | 0.51    | -6.44   | -45.80  | 9800 $\times$ 381     |
|                        | $5.5 \times 5.5$       | 0.11    | -6.14   | -43.47  | 8600 $\times$ 381     |
|                        | $5 \times 5$           | 0.06    | -6.26   | -39.42  | 7100 $\times$ 381     |
| $1 \times 8$           | $6 \times 6$           | 1.16    | -9.56   | -45.65  | 20300 $\times$ 889    |
|                        | $5.5 \times 5.5$       | 0.32    | -9.34   | -43.69  | 18600 $\times$ 889    |
|                        | $5 \times 5$           | 0.29    | -9.42   | -40.44  | 15600 $\times$ 889    |
| $1 \times 16$          | $6 \times 6$           | 1.36    | -12.92  | -45.80  | 38800 $\times$ 1905   |
|                        | $5.5 \times 5.5$       | 0.67    | -12.57  | -44.66  | 33600 $\times$ 1905   |
|                        | $5 \times 5$           | 0.32    | -40.69  | -42.52  | 27100 $\times$ 1905   |
| $1 \times 32$          | $6 \times 6$           | 1.58    | -16.13  | -46.73  | 66800 $\times$ 3937   |
|                        | $5.5 \times 5.5$       | 0.89    | -15.82  | -45.53  | 55600 $\times$ 3937   |
|                        | $5 \times 5$           | 0.46    | -15.69  | -42.52  | 43100 $\times$ 3937   |
| $1 \times 64$          | $6 \times 6$           | 1.90    | -19.28  | -46.81  | 103800 $\times$ 8001  |
|                        | $5.5 \times 5.5$       | 1.23    | -19.05  | -46.24  | 83600 $\times$ 8001   |
|                        | $5 \times 5$           | 0.70    | -18.91  | -43.06  | 61100 $\times$ 8001   |

Properties and the length of the highest obtained $1 \times 64$ Y-branch splitter are described as follows: The non-uniformity ($ILu$) of the $(5.5 \times 5.5) \mu m^2$ core size-optimized splitter was reduced from 1.9 dB to 1.23 dB what is 35.26 % improvement of the initial non-uniformity value reached for a conventional splitter with $(6 \times 6) \mu m^2$ core size. In the case of the core size $(5 \times 5) \mu m^2$, the non-uniformity was decreased to value 0.7 dB, which is an improvement of 63.16 % compared to the non-uniformity of the splitter with a standard waveguide core size of $(6 \times 6) \mu m^2$. The insertion loss ($IL$) for core size $(6 \times 6) \mu m^2$ is -19.28 dB. In both cases of the waveguide core size optimization, the insertion loss also improved slightly. The background crosstalk ($BX$) is very similar for core sizes $(6 \times 6) \mu m^2$ and $(5.5 \times 5.5) \mu m^2$. For a $(5 \times 5) \mu m^2$ core size, the background value increased by 8.01 % compared to waveguide core size of $(6 \times 6) \mu m^2$. Together with a linear input and output ports, the entire size of the $1 \times 64$ Y-branch splitter with core size $(6 \times 6) \mu m^2$ reached $(103800 \times 8001) \mu m^2$, where 103800 $\mu m$ is the length and 8001 $\mu m$ is the width of the splitter. In both cases of core size reduction, the simulation results show, that the length of the final splitter was significantly reduced compared to the length of optical splitters with $(6 \times 6) \mu m^2$ core size. The entire size of the $1 \times 64$ Y-branch splitter with core size $(5.5 \times 5.5) \mu m^2$ reached $(83600 \times 8001) \mu m^2$ and for a core size $(5 \times 5) \mu m^2$ $(61100 \times 8001) \mu m^2$, what is nearly half of the original splitter length.

Figures 5a–d show the dependence of the splitting parameters on the number of output ports of the designed Y-branch splitters. Figure 5a shows non-uniformity dependence on the number of output ports. As can be seen, in every splitting property of $1 \times 2$ till $1 \times 64$ Y-branch splitters with each reduction of the core size, the non-uniformity was improved significantly. In some cases, the non-uniformity was improved by more than half of the original value. Equally, significant improvement is shown in Fig. 5d, where the length of the splitters depends on the
number of outputs. The obtained length of $1 \times 64$ Y-branch splitter for a standard $(6 \times 6)$ $\mu$ m$^2$ core size was 103800 $\mu$m. With the reduction of the waveguide core size on $(5.5 \times 5.5)$ $\mu$ m$^2$, the length of the $1 \times 64$ Y-branch splitter reached 83600 $\mu$m, which was 20200 $\mu$m less than the $1 \times 64$ Y-branch splitter with a standard $(6 \times 6)$ $\mu$ m$^2$ waveguide core size. By reducing the waveguide core size to $(5 \times 5)$ $\mu$ m$^2$, the length of the splitter was reduced by up to 42700 $\mu$m, which is a 41.14 % improvement over the standard waveguide core size of $(6 \times 6)$ $\mu$ m$^2$. As presented in Fig. 5b, insertion loss also improved with decreasing core size but not that substantially, compared to other optical properties. The simulated insertion loss values did not differ much from the theoretical value, however as expected, the maximum difference (1.28 dB) was reached in the case of the $1 \times 64$ Y-splitter with the standard waveguide core size of $(6 \times 6)$ $\mu$ m$^2$ and the minimum difference (0.91 dB) was reached when the waveguide core size was reduced to $(5 \times 5)$ $\mu$ m$^2$. Background crosstalk presented in Fig. 5c shows only a slight increase with the increasing number of output ports for every core size. The highest values of background, which means the best background performance have the splitters with the waveguides of $(6 \times 6)$ $\mu$ m$^2$ core size. On the other side, the lowest values of background are reached with $(5 \times 5)$ $\mu$ m$^2$ core size, which is insignificant given the excellent final performance of other optical properties as a non-uniformity, insertion loss, and waveguide length.
5 Conclusion

The Y-branch optical splitters up to a high symmetric port-count of 64 with a standard \((6 \times 6) \mu m^2\) cross-section have been designed, simulated, and length optimized. They were designed for the low refractive index contrast material (silica-on-silicon), for a telecommunication wavelength of 1550 nm. To support only single-mode propagation, the waveguide core size has been decreased to \((5.5 \times 5.5) \mu m^2\) and \((5 \times 5) \mu m^2\). With the decreased waveguide core size, the better beam splitting performance such as non-uniformity and insertion losses were achieved. On the other hand, the performance of background crosstalk was increasing with the reduction of the waveguide core size. For both waveguide core sizes, the length of the Y-branch splitters has been optimized as well. The simulations showed that the reduction of waveguide core size leads not only to significant improvement of the optical properties but also to a much smaller footprint of the Y-branch splitters.

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