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PAPERS

Design and optimization of 1×2^N Y-branch optical splitters for telecommunication applications

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This paper presents the design and optimization of 1×2^N Y-branch optical splitters for telecom applications. A waveguide channel profile, used in the splitter design, is based on a standard silica-on-silicon material platform except for the lengths of the used Y-branches, design parameters such as port pitch between the waveguides and simulation parameters for all splitters were considered fixed. For every Y-branch splitter, insertion loss, non-uniformity, and background crosstalk are calculated. According to the minimum insertion loss and minimum non-uniformity, the optimum length for each Y-branch is determined. Finally, the individual Y-branches are cascade joined to design various Y-branch optical splitters, from 1×2 to 1×64.

K e y w o r d s: 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 to distribute an optical signal. Thus, an optical distribution infrastructure consists only of passive optical components such as optical fibers, connectors, and optical splitters. 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 [1]. Based on the 50%:50% beam-splitter formalism, a perfect two-way passive splitter would provide half as much beam power *ie*, -3 dB to each output port [2]. One of the mostly 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 [3]. The Y-branch optical splitters are commonly used in network architectures, as Fiber-To-The-× (FTTx) because of two main advantages: they are polarization and wavelength independent *ie*, they can be used in the whole telecommunication-operating window. This technology enables high-speed broadband connections simultaneously to multiple users at home, businesses and other establishments.

The main challenges in the design of Y-branch optical splitters are the asymmetric splitting ratio (non-uniformity) of split 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.

We present a summary of the related works. Given the details on the design and simulation parameters, the influence of the waveguide length on the final performance of Y-branch optical splitters is examined and optimization is achieved. After describing the mathematical analysis of the simulated results we critically assesses achieved results.

2 Related works

Over the past years, several passive integration techniques have been developed. In this section, relevant work addressing a 1×64 Y-branch splitter, the highest reached splitter in this paper, is introduced. For the mathematical analysis, the beam propagation method was used for all the below-related works.

One of the first 1×64 splitters has been reported by Tsuda *et al* in 2008 [4], where they used two approaches: the conventional Y-branch circuit and the Y-branch circuit with taper waveguide between a filter cutting the higher-order mode and the input waveguide. The used material was silica-based Planar Waveguide Circuit (PLC) on quartz substrate. The refractive index contrast between cladding and core was $\Delta n = 0.4$ % and the waveguide core size was 7×7 μm^2. They fabricated the 1×64 splitter module with the insertion loss less than -19.3 dB, the non-uniformity $(ILu) < 0.7$ dB for the

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wavelength of 1.31 μm and 1.55 μm. The obtained chip size was 27500×9500 μm^2.

Wand *et al* in 2014 [5] proposed a similar low wavelength dependence loss 1×64 optical power splitter, which was fabricated using silica-based PLC technology on a quartz substrate. The Y-branch splitter was designed with the refractive contrast between the cladding and core $\Delta n = 0.45$ %, and the refractive index of core $n_c =$ 1.4515 and cladding n_{cl} =1.455. The waveguide core size was 6.5×6.5 μm^2, to ensure a single mode propagation. The splitter was designed with 127 μm port pitch. The best results of the splitter achieved the insertion loss of less than -19.2 dB and non-uniformity less than 1.0 dB, in the wavelength range from 1.26 μm to 1.65 μm. They achieved a large improvement of optical characteristics by optimizing the tilt of Y-branch, compared to the proposed structure by Toshiaki Tsuda in 2008 [4]. Because of the small bend radius and the sparkle cascading style, the final dimension of the chip was only 21000× 8600 μm^2, which was 6500 μm shorter than that of the splitter reported by Toshiaki Tsuda [4].

In the same year, Burtscher *et al* [6] presented a 1×64 Y-branch splitter with the same design parameters and material of the waveguide as are presented in this paper. The refractive indices and used material are described in Section 3. They proposed the design of the splitter by doubling each additional Y-branch from the previous one to keep the same bending shape. Their Y-branch splitter achieved the insertion loss -19.89 dB and non-uniformity was 2.67 dB with the background crosstalk $BX = -42.24$ dB. The size of the splitter reached 318000 ×8001 μm^2. They tried to optimize the length of the splitter, but any length reduction caused the worsening of optical parameters as the insertion loss about -22 dB and the non-uniformity of more than 4 dB.

3 Design and optimization of 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 higher-index optical medium, called core, which is transversely surrounded by lower-index media, called cladding [7]. 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 $n_c = 1.445$ and refractive index of cladding n_{cl} = 1.456 at wavelength, $\lambda = 1550$ nm. The size of the waveguide was set to 6×6 μm^2 [6, 8-9].

Figure 1(a) shows the design of standard 1×4 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 μm. This spacing is required for a connection with the fibers. This initial pitch value is then doubled with every further layer, $L(n)$. One of the main sources of the losses that occurs in the Y-branch splitter is the branching point. Each individual Y-branch is constructed of two waveguides having a predefined cosine arc S-shape called "s-bend-arc". Based on the Y-branch geometries which have been explored in [10, 11], this shape is supposed to provide the least losses. 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. 1(b). From the graph, it is evident that the optical power between the length of 700 μm and 2100 μm is damped. In this length range, the waveguides feature a steeper angle of the waveguide 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. In this case, the bending loss is significantly reduced approximately at 2800 μm length. Therefore, the length of the first Y-branches $L(1^{st})$ is set to 2800 μm.

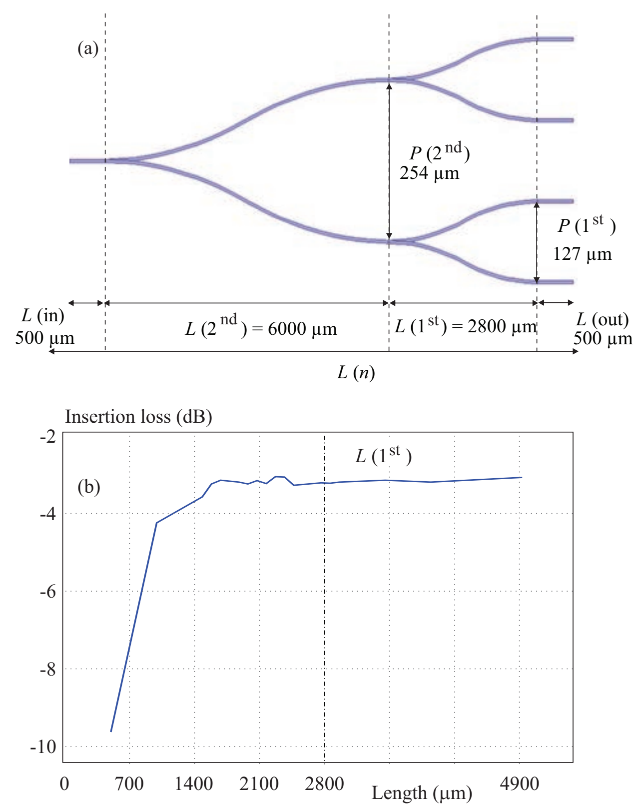

Fig. 1. (a) – schematic view of the proposed 1×4 Y-branch optical splitter with its design parameters, (b) – scanning of the length of the branches based on the minimum bending losses

After scanning the lengths $L(n)$ of all Y-branches for all particular port pitches $P(n)$, shown in Tab. 1, the Y-branches were joined together to create the final 1×2^N splitters. For instance, the 1×4 Y-branch splitter structure contains one Y-branch with a 254 μm port pitch followed by two Y-branches with 127 μm pitch as presented in Fig. 1(a). Such a cascade arrangement 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 1×8, 1×16, 1×32, and even more complex splitting structures, like 1×64 Y-branch optical splitters.

Table 1. Summary of widths and lengths of Y-branch layers in the 1×64 splitter

Pitch	(μm)	Length	(μm)
$P(1^{st})$	127	$L(1^{st})$	2800
$P(2^{nd})$	254	$L(2^{nd})$	6000
$P(3^{rd})$	508	$L(3^{rd})$	10500
$P(4^{th})$	1016	$L(4^{th})$	18500
$P(5^{th})$	2032	$L(5^{th})$	28000
$P(6^{th})$	4064	$L(6^{th})$	37000

Two-dimensional BPM isotropic simulation was performed for every 1×2^N Y-branch splitter. The 2D BPM simulator is based on the finite difference method algorithm of Crank-Nicolson [12]. 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 [13]. 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. The waveguide with TE polarization is dependent on the transverse electric waves and their electric field vector is being always perpendicular to the direction of the propagation. Figure 2 shows the design of the highest reached splitting ratio, 1×64 Y-branch splitter.

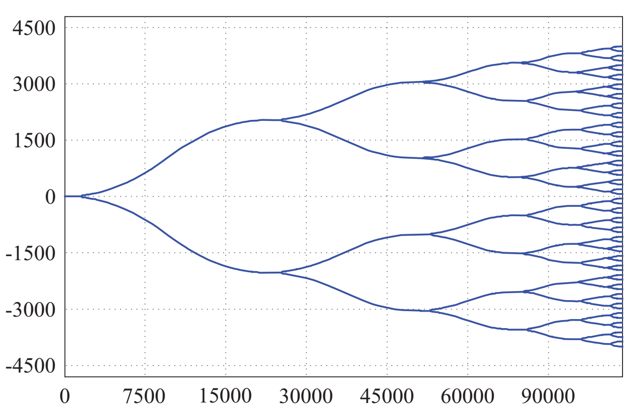

Fig. 2. Design of 1×64 Y-branch optical splitter with OptiBPM photonics tool by Optiwave

4 Formulas

Design and simulation of passive optical components are performed by a commercial photonic tool BeamPROP from Optiwave. This tool uses the Beam Propagation Method (BPM) based on the parabolic or paraxial approximation of the Helmholtz equations. Such a model then simplifies the simulations, reduces the processing time, and better manages the computer memory [12].

Telcordia GR1209 & GR-1221 standards outline the generic criteria for the passive optical components to determine the quality of the PLC splitters over their product lifecycle. The standards specify general requirements for an outside plant component, the functional criteria, and the performance criteria [14]. For simulation purposes to evaluate the optical performance of the proposed splitters, the criteria as non-uniformity, insertion loss, and background crosstalk are essential, and therefore they were calculated. For symmetrical Y-branches, the optical power at each output port is approximately half of the optical power from the input port. The output signals have theoretically an equal amplitude, 0° phase relationship between any two output signals, and high isolation between each output signal [15]. The theoretical insertion loss [16] in decibels is taken as

$$L_{\mathrm{dB}} = 10\log N, \tag{1}$$

where N is the number of output ports. In case of a simple 1×2 Y-branch splitter, the theoretical insertion loss is $10\log 2 = 3$ dB. Table 2 shows mathematically defined theoretical insertion loss based on the number of output ports.

Table 2. Theoretical insertion loss for number of output ports

No. of output ports	Theoretical insertion loss dB
2	3
4	6
8	9
16	12
32	15
64	18

The fraction of power transferred from the input port to the output port ie, insertion loss (IL) [17] is calculated after simulation for each port separately by:

$$IL = -10\log\sum_{i=1}^{N}\frac{I_i}{I_{in}}, \tag{2}$$

where I_i is the output energy from the i-th output waveguide, and I_{in} is the energy at the input waveguide. The maximum insertion loss is taken as a final insertion loss of the whole designed splitter.

Another parameter which was calculated is insertion loss uniformity [18] ILu, (also called non-uniformity),

Table 3. Summary of splitting parameters achieved from the simulations of 1×2^N Y-branch splitter with waveguide core size $6\times 6\ \mu\text{m}^2$

splitters 1×2^N	non -uniformity ILu (dB)	insertion loss IL (dB)	background crosstalk BX (dB)	chip size (μm^2)
1×2	0.00	-3.17	-43.38	3800×127
1×4	0.51	-6.44	-45.80	9800×381
1×8	1.16	-9.56	-45.65	20300×889
1×16	1.36	-12.92	-45.80	38800×1905
1×32	1.58	-16.13	-46.73	66800×3937
1×64	1.90	-19.28	-46.81	103800×8001

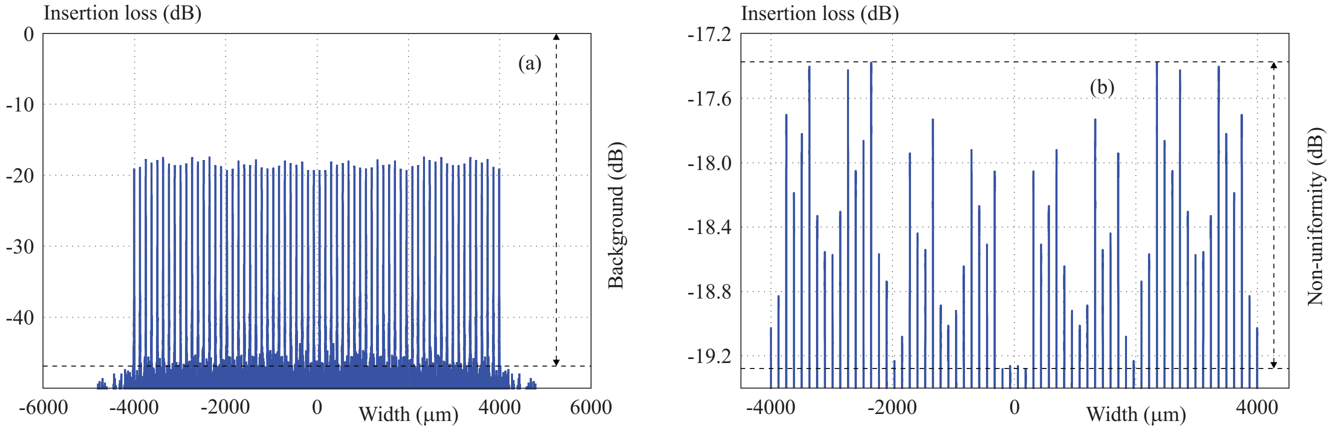

Fig. 3. Simulation results of 1×64 Y-branch splitter structure with OptiBPM photonics tool by Optiwave: (a) – field distribution at the end of simulated structure together with a background crosstalk (BX), (b) – detailed view of field distribution showing the non-uniformity (ILu) and the insertion loss (IL)

which measures the difference between the maximum and minimum of insertion loss (Ii) of the optical signal

$$ILu = 10\log\left[\frac{\min(I_i)}{\max(I_i)}\right]. \qquad (3)$$

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 two values.

5 Results and discussion

Table 3 shows the splitting parameters and final sizes of the length-optimized Y-branch optical splitters with splitting ratio 1×2, 1×4, 1×8, 1×16, 1×32, and 1×64. As can be seen, the length-optimized splitters feature a small footprint as well as outstanding optical performance.

Figure 3(a) shows the field distribution achieved at the end of the simulation, together with background crosstalk of the highest splitting ratio 1×64 Y-branch splitter. The maximum background crosstalk is $BX = -46.81$ dB. Figure 3(b) shows how the propagation signals are divided at the output. The insertion loss reached value $IL = -19.28$ dB. The insertion loss is less than -20 dB, which complies with the commercial requirements [19], and it is also less than the acceptance limit of Telcordia Technologies Generic requirements. Figure 3(b) also shows the achieved non-uniformity between maximum and minimum insertion losses, which is 1.9 dB. Together with a linear input and output ports, the entire size of the 1×64 Y-branch splitter reached $103800\times 8001\ \mu\text{m}^2$.

The following Figs. 4(a)-4(c) show the dependence of the splitting parameters on the number of output ports (N = 2, 4, 8, 16, 32, and 64) of all designed Y-branch splitters. As presented, when increasing the number of output ports, the non-uniformity has a significant influence on the optical properties of 1×2 to 1×16 Y-splitters. With further increase of the output ports ie 1×32 and 1×64, the non-uniformity does not increase significantly. The difference between theoretical and simulated insertion loss for all simulated splitters is presented in Fig. 4(b). The theoretical insertion loss for each splitter is considered with zero non-uniformity, which means the optical signal is split equally at all Y-branching points. The simulated losses depend not only on the non-uniformity of the split signal, but also on propagation losses, and bending losses. The maximum difference between the theoretical and simulated insertion loss is 1.28 dB for a 1×64 Y-splitter, and minimum insertion loss differs in the case

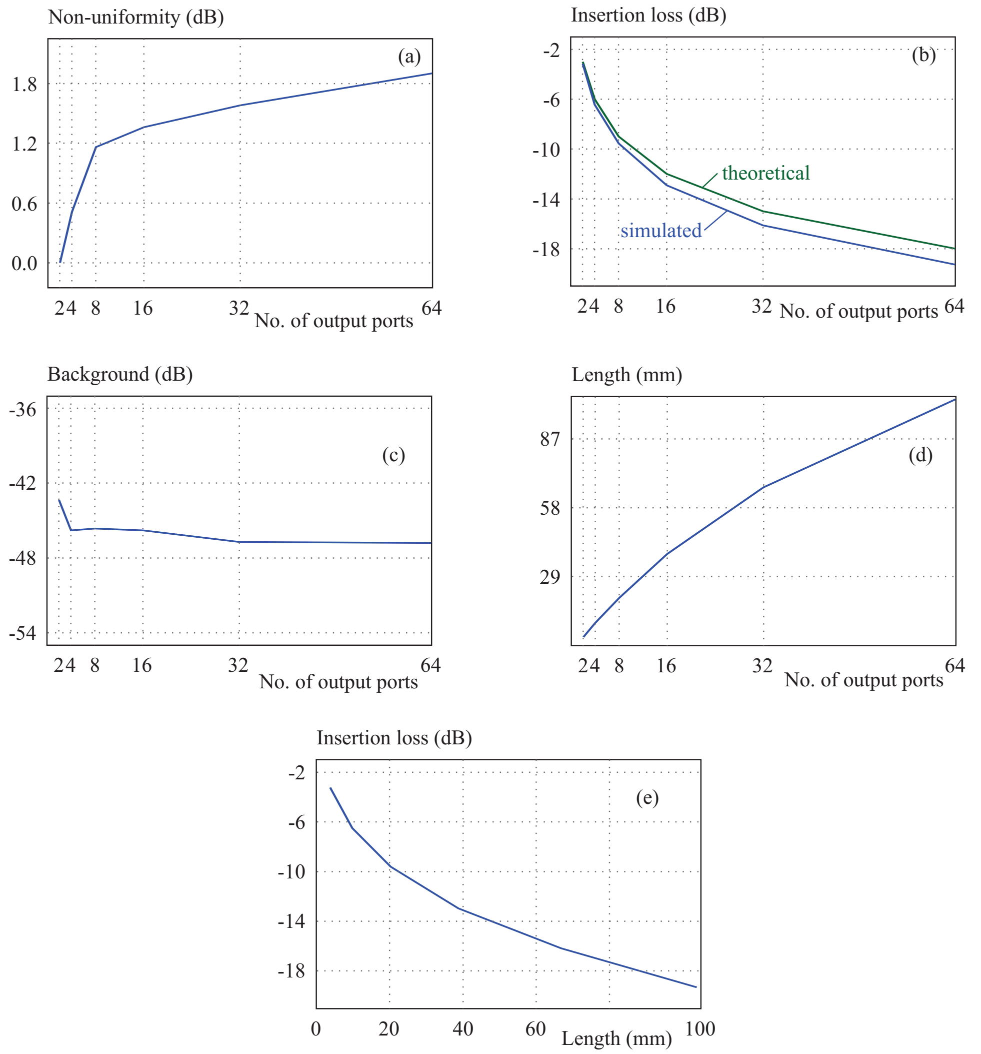

Fig. 4. Results comparison of 1×2^N Y-branch splitters parameters with OptiBPM photonics tool by Optiwave: (a) – non-uniformity dependency on increasing number of output ports, (b) – comparison of simulated and theoretical insertion loss on increasing number of output ports, (c) – background dependency on increasing number of output ports, (d) – length dependency of Y-branch splitters on increasing number of output ports, (e) – insertion loss dependency on the length ratio of Y-branch splitters

of the 1×2 Y-splitter by 0.17 dB. Background crosstalk presented in Fig. 4(c) shows only a slight increase with the increasing number of output ports. In Fig. 4(d) can be seen that the length of individual Y-branch splitters increases almost linear each time the number of ports was doubled. Figure 4(e) shows the dependency of the insertion loss on the length of the optimized Y-branch splitters. This dependency is similar to the dependency in Fig. 4(b). The insertion loss is increasing exponentially with the growing length of the Y-branch splitters as well as with the increasing number of the output ports because the length and number of output ports are dependent on each other.

6 Conclusion

Design and optimization of 1×2^N Y-branch optical splitters up to 64 output ports based on silica-on-silicon material platform for telecommunication applications were proposed. The structure of each splitter was optimized to reach the shortest possible length and good optical performance. The length-optimized optical splitters were simulated, and the results confirm very low insertion losses and high uniformity of the split optical beam at output waveguides. In this paper, the better optical performance of a 1×64 Y-branch splitter was achieved compared to the mentioned designed and optimized splitter in the related work by Burtscher *et al* [6], who used the same design parameters. Instead of doubling the lengths of Y-branches from the previous layer, each branch was optimized individually in this work. The insertion loss was then reduced by 0.61 dB, non-uniformity was also reduced by 0.77 dB, and background crosstalk was lower by 4.47 dB. The final dimension of the chip was only 103800×8001 μm^2, which was 214200 μm shorter than the splitter reported by Burtscher *et al* [6].

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Heinz Seyringer studied physics and mathematics at the Swiss Federal Institute of Technology (ETH) and made his PhD in semiconductor physics. In 2000 he joined Photeon Technologies, an optical chip design company focused on passive optical devices, where he became general manager. From 2009 until 2017 he was with the Zumtobel Group, a leading player in the lighting industry, and since 2017 he is CEO of V-Research, an industrial research institute focused on Photonics, Digital Engineering, and Tribology, and since 2019 he is additionally head of research of the University of Applied Sciences Vorarlberg. He is also a member of the executive board of the European photonics platform, Photonics21, a former member of the board of directors of the European Photonics Industry Consortium (EPIC), and chairman of the Austrian photonics platform, Photonics Austria.

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