Modeling and optimization of 1×32 Y-branch splitter for optical transmission systems

Catalina Burtscher^{1,3} · Dana Seyringer¹ · Anton Kuzma² · Michal Lucki³

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Abstract The goal of this paper is to design a low-loss 1×32 Y-branch optical splitter for optical transmission systems, using two different design tools employing Beam Propagation Method. As a first step, a conventional 1×32 Y-branch splitter was designed and simulated in two-dimensional environment of OptiBPM photonic tool. The simulated optical properties feature high loss, high asymmetric splitting ratio and a large size of the designed structure, too. In the second step of this work we propose an optimization of the conventional splitter design leading to suppression of the asymmetric splitting ratio to one-third of its initial value and to the improvement of the losses by nearly 2 dB. In addition, 50% size reduction of the designed structure was also achieved. This length-optimized low-loss splitter was then modelled in a three-dimensional environment of RSoft photonic tool and the simulated results confirm the strong improvement of the optical properties.

Keywords Y-branch splitter · Optical splitting · Optical Access Networks (OAN) · Optical Network Unit (ONU) · Passive Optical Networks (PON) · Fibre-to-the-x (FTTx) networks

✉ Catalina Burtscher
burtscat@fel.cvut.cz

Dana Seyringer
dana.seyringer@fhv.at

¹ Research Center for Microtechnology, Vorarlberg University of Applied Sciences, Hochschulstr. 1, 6850 Dornbirn, Austria

² International Laser Centre, Ilkovicova 3, Bratislava 84104, Slovak Republic

³ Department of Telecommunication, Faculty of Electrical Engineering, Czech Technical University in Prague, Technická 2, Dejvice, Prague 16627, Czechia

1 Introduction

Optical Access Networks (OANs) usually employ the tree topology to propagate signals from the Optical Line Terminal (OLT) to subscribers at Optical Network Units (ONUs). The propagation of optical beams from an OLT to ONUs can be implemented by using optical splitters (Lam 2007). Splitters are important elements in Passive Optical Networks (PONs), in terms of potential reduction of the financial expenses (Grobe and Elbers 2008).

There are two main approaches used to split one input optical signal into N output signals. In multimode interference (MMI) splitters, the splitting of the optical signal is based on a self-imaging effect appearing inside the multimode section (Bryngdahl 1973).

Fig. 1 Top view of the 1×4 Y-branch splitter structure designed in OptiBPM photonic tool

Fig. 2 Top view of 1×32 Y-branch conventional splitter designed in OptiBPM photonic tool

By cutting the splitter at a particular length, L_{MMI} , N output signals can be obtained. The MMI splitters feature a large splitting number and stable symmetric splitting ratio (Rasmussen et al. 1995), ensuring good uniformity over all the output signals. Furthermore, the MMI splitters are potentially shorter in comparison to Y-branch splitters (Rasmussen et al. 1995). Another advantage is their good fabrication tolerance because the splitting is performed in the multimode section. Their main disadvantage results from the fact that the length of the multimode section is wavelength dependent, i.e. the MMI splitters are designed solely for one wavelength and can only operate in a narrow wavelength band. They are also polarization dependent; however, it has been shown that for strong guidance waveguide structures this dependence is negligible (Bachmann et al. 1993).

In contrast to this approach, the Y-branch splitters use a cascade of one-by-two waveguide branches (also called Y-branches) (Nourshargh et al. 1989). Anyhow, the processing of the branching point, where two waveguides start to separate, is technologically very difficult (Soldano et al. 1992). This generally leads to an asymmetric splitting ratio causing non-uniformity of the split power over all the output waveguides. Additionally, to keep the losses as low as possible the curvature of the Y-branches has to be low, leading to a rather long chip size. On the other hand, Y-branch splitters have the advantage that they are polarization and wavelength independent, i.e. one device can be used to split optical signals in the whole operating wavelength window. This is one of the main reasons why Y-branch splitters are broadly deployed in Fibre-to-the-x (FTTx) technology.

In this paper, we focus on the design, simulation and optimization of low-loss and small-size 1×32 Y-branch splitters employing two commercially available software tools.

Fig. 3 Top view of the simulated conventional 1×32 Y-branch splitter structure applying OptiBPM photonic tool

Fig. 4 1×32 Y-branch conventional splitter (OptiBPM simulation): **a** field distribution at the output of the modeled splitter and the background isolation, BX ; **b** detailed view of the field displaying the non-uniformity, ILu and the insertion loss, IL

2 Design of conventional 1×32 Y-branch splitter applying OptiBPM photonic tool

The design of 1×32 Y-branch splitter is focused on weakly guiding silica waveguides with the refractive index of the cladding being $n_{cl} = 1.445$ and of the core respectively $n_c = 1.456$, with the index contrast, $\Delta n = 0.75\%$, which matches well the index contrast of standard optical fibers. Considering the core dimensions, we prefer conventional $(6 \times 6) \mu\text{m}^2$ waveguide cross-section. The proposed 1×32 Y-branch splitter is designed for operating wavelength $\lambda = 1.55 \mu\text{m}$ and simulated employing the Beam Propagation

Fig. 5 Top view of 1×32 Y-branch length-optimized splitter designed **a** and simulated **b** in OptiBPM photonic tool

Method in two-dimensional OptiBPM photonic tool from Optiwave Systems Inc (Optiwave 2017).

The design of 1×32 Y-branch splitter is based on the design of 1×4 optical splitter as displayed in Fig. 1. The branches of this splitter were modeled with the use of a reference “s-bend-arc” branch shape, since this shape provides the best results from all predefined standard geometries (Burtscher and Seyringer 2014). The outputs of the branches are

Fig. 6 1×32 Y-branch length-optimized splitter: **a** field distribution at the output waveguides together with the background isolation, BX ; **b** detailed view of the field displaying the non-uniformity, ILu and the insertion loss, IL (OptiBPM)

selected to be $6 \mu\text{m}$ width since we used $(6 \times 6) \mu\text{m}^2$ size of the waveguide core. The length of the linear input port is considered $1000 \mu\text{m}$. A $127 \mu\text{m}$ pitch, necessary for launching the fibres, is proposed for the output waveguides port pitch. Moreover, the length of output ports is $2000 \mu\text{m}$. The length of the second branch is $L(2nd) = 5000 \mu\text{m}$, which is an optimal length, tested in a number of runs: the conclusion is that for longer branches

Fig. 7 Top view of the conventional 1×32 Y-branch splitter structure designed applying RSoft photonic tool

(ensuring weaker bending) no improvement of optical properties was observed. On the other hand, shorter branches (leading to stronger bending) caused the rise of the transmission losses (Burtscher and Seyringer 2014). To maintain the same bending, the length of the first branch was set $L(1st) = 10,000 \mu\text{m}$ (twice the initial length of the second branch). The spacing between the waveguides in this branch was also doubled, $W(1st) = 254 \mu\text{m}$. The described 1×4 Y-branch splitter design was later employed to design 1×8 or 1×16 Y-branch splitters to study their optical properties (Burtscher and Seyringer 2014).

The 1×32 Y-branch splitter design employs the model of 1×16 Y-branch splitter. It is composed of two 1×16 splitters combined by an extra waveguide Y-branch, as depicted in Fig. 2. The splitter has one linear input port, 32 linear output ports and 31 branches that are spread in five layers. Based on the design described above, the 1st branch layer is $L(1st) = 5000 \mu\text{m}$ and the second branch layer is doubled, $L(2nd) = 10,000 \mu\text{m}$. To keep the bending shape, each subsequent branch layer was doubled, too, i.e. $L(3rd) = 20,000 \mu\text{m}$, $L(4th) = 40,000 \mu\text{m}$ and $L(5th) = 80,000 \mu\text{m}$. With decreasing number of branches in particular layers, the spacing between the waveguides in each branch layer is also doubled, i.e. in the 1st branch layer $W(1st) = 127 \mu\text{m}$, in the 2nd branch layer $W(2nd) = 254 \mu\text{m}$, ..., in the 5th branch layer $W(5th) = 2032 \mu\text{m}$. The entire 1×32 Y-branch splitter reached the length of $158,000 \mu\text{m}$ and the width of the structure is equal to $3937 \mu\text{m}$ ($= 31 \times 127 \mu\text{m}$). For simplification purposes, we will refer to this structure as “conventional splitter”.

3 Simulation of conventional 1×32 Y-branch splitter applying OptiBPM photonic tool

The simulation of conventional 1×32 Y-branch splitter was performed in two-dimensional environment of OptiBPM tool. Figure 3 presents the top view of the simulated structure, featuring the scattered light at the branching points that causes losses in the structure.

Figure 4 displays the simulated optical properties of this splitter. Figure 4a shows the field distribution at the output waveguides. It can be observed that the background

Fig. 8 Detailed view of the field distribution displaying the non-uniformity, ILu and the insertion loss, IL (applying RSoft photonic tool): **a** conventional 1×32 Y-type splitter (6×6) μm^2 ; **b** length-optimized 1×32 Y-branch splitter with the core dimensions (5.5×5.5) μm^2

isolation, BX is better than -40.0 dB. The uniformity of the split power over all the outputs (difference between the highest and the lowest peak, also known as non-uniformity), $ILu = 3.68$ dB and the insertion loss (the lowest peak in the distribution) $IL = -18.35$ dB, as shown in Fig. 4b).

4 Optimization of conventional 1×32 Y-branch splitter design

As can be observed from the results the proposed conventional 1×32 Y-branch splitter is not only very long, but it suffers from high non-uniformity and high insertion losses, too. In particular, the non-uniformity ILu with more than 3 dB is rather high, causing also high non-uniformity. The detailed study of the results indicated that the essential reason for such high non-uniformity is the presence of the first mode (besides the fundamental mode) in the (6×6) μm^2 waveguides. To solve this issue, we designed the same splitter structure, but with a smaller waveguide core size, particularly (5.5×5.5) μm^2 . The result of such optimization is a strong improvement of the optical properties of the splitter, offering the possibility to reduce the length of the designed conventional splitter from 158,000 μm to 86 000 μm (as presented in Fig. 5). For the simplicity, we will refer to this splitter as “length-optimized”. The simulation results of this splitter are shown in Fig. 6. The non-uniformity, ILu is less than one-third of the initial non-uniformity value reached for the conventional splitter (ILu was 3.68 dB), namely $ILu = 1.12$ dB. The insertion loss decreased from $IL = -18.35$ dB to $IL = -16.17$ dB and the length of the splitter shrank almost to 50% of its original length (from 158,000 μm to 86,000 μm).

5 Design and simulation of 1×32 Y-branch splitters applying RSoft photonic tool

The conventional 1×32 Y-branch splitter with the waveguide core size (6×6) μm^2 was then designed and simulated in three-dimensional environment of RSoft photonic tool (2017). The top view of the structure is presented in Fig. 7. The optical properties are displayed in Fig. 8a. The non-uniformity, $ILu = 2.15$ dB and the insertion loss, $IL = -16.44$ dB.

Finally, the length-optimized splitter with the core size (5.5×5.5) μm^2 was designed and simulated and the results are displayed in Fig. 8b). The non-uniformity, $ILu = 0.26$ dB and the insertion loss $IL = -15.33$ dB.

6 Discussion of the results

Table 1 summarizes the results achieved from all designed and simulated 1×32 Y-branch splitters. From the results is evident that the reduction of the waveguide core size leads to the significant improvement of the optical properties of the splitters. Namely the non-uniformity decreased from $ILu = 3.68$ dB (conventional splitter) to 1.12 dB (length-

Table 1 Summary of the simulation results obtained with both photonic tools

Waveguide core size	1 × 32 Y-branch splitter					
	OptiBPM			RSoft		
	Conventional (6 × 6 μm ²)	Length-optimized (5.5 × 5.5 μm ²)	Improvement Δ	Conventional (6 × 6 μm ²)	Length-optimized (5.5 × 5.5 μm ²)	Improvement Δ
Non-uniformity, <i>IL_u</i>	3.68 dB	1.12 dB	2.56 dB	2.15 dB	0.26 dB	1.89 dB
Insertion loss, <i>IL</i>	– 18.35 dB	– 16.7 dB	1.65 dB	– 16.44 dB	– 15.33 dB	1.11 dB
Chip size	158,000 μm	86,000 μm	72,000 μm	158,000 μm	86,000 μm	72,000 μm

optimized splitter) applying OptiBPM tool, which is one-third of original loss of conventional splitter. The loss was reduced from -18.35 dB to -16.7 dB. The splitters designed and simulated in three-dimensional environment of RSoft tool feature even more satisfying results: the insertion loss IL was suppressed from -16.44 dB (conventional splitter) to -15.33 dB (length-optimized structure) and the non-uniformity, ILu from 2.15 dB (conventional structure) to 0.26 dB (length-optimized structure), which is nearly one tenth of the original value.

7 Conclusion

In this paper we proposed the optimization of conventional 1×32 Y-branch splitter to improve its optical properties (length-optimized splitter). To this purpose, we used two different photonic tools, OptiBPM and RSoft tool. From the simulations is evident that the reduction of the waveguide core size from $(6 \times 6) \mu\text{m}^2$ to $(5.5 \times 5.5) \mu\text{m}^2$ leads to significant improvement of optical properties of the designed splitters. Namely, the insertion losses were suppressed by $\Delta IL = 1.65$ dB (OptiBPM tool), and by $\Delta IL = 1.11$ dB (RSoft tool) (Table 1). Similarly, we reached symmetric splitting ratio, ensuring good uniformity over all the output signals, $\Delta ILu = 2.56$ dB (OptiBPM) and $\Delta ILu = 1.89$ dB (RSoft). Additionally, our proposed optimization led to the length reduction of the conventional splitter almost to the half of the original value (length-optimized splitter). It is also important to point out that the further reduction of the waveguide core size to $(5 \times 5) \mu\text{m}^2$ did not bring any further significant improvement of the parameters compared to length-optimized splitter having core size $(5.5 \times 5.5) \mu\text{m}^2$.

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