An MMI-Based 4-Beam Combiner with Spline-Curved Index Step

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Abstract

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Abstract: We propose a compact MMI-based 4-beam combiner with a spline-curved index step. The 1.74 mm-long device designed in InP material systems offers 3 dB better transmittance than power combiners at a 4.5 nm wavelength spacing.

OCIS codes: 230.1360 Beam splitter; 130.7408 Wavelength filtering devices; 230.3120 Integrated optics devices.

1. Introduction

InP-based photonic integrated circuits (PIC) have received much attention to monolithically integrate lasers, modulators, and wavelength combiners, to realize high performance and compact transmitters for wavelength division multiplexing optical communications. One of such applications is an optical Ethernet, where multiple wavelengths are combined into a single fiber [1].

A power combiner based on multi-mode interference (MMI) [2] has been used conventionally. Although its design and fabrication processes are well established, there is an inherent $3N$ dB insertion loss for $2^N \times 1$ coupling (N is a positive integer). Alternatively, 1×2 MMI-based wavelength splitters have been reported [3], whereas the device length needs to be long for narrow wavelength spacing. A 1×2 wavelength splitter using silicon slot waveguide was proposed [4], although slot waveguides cannot be readily applied to InGaAsP/InP material systems. An InP-based compact 4×4 arrayed waveguide grating (AWG) was fabricated [5] using deep reactive ion etching process. An InP-based 1×2 Mach-Zehnder interferometer (MZI) is another solution for wavelength coupler/splitter [6]. A compact 1×4 wavelength combiner/splitter has been demonstrated based on ring resonators on silicon-on-insulator platform [7]. However, this is not directly applicable to InGaAsP/InP material systems, where very sharp bending is infeasible.

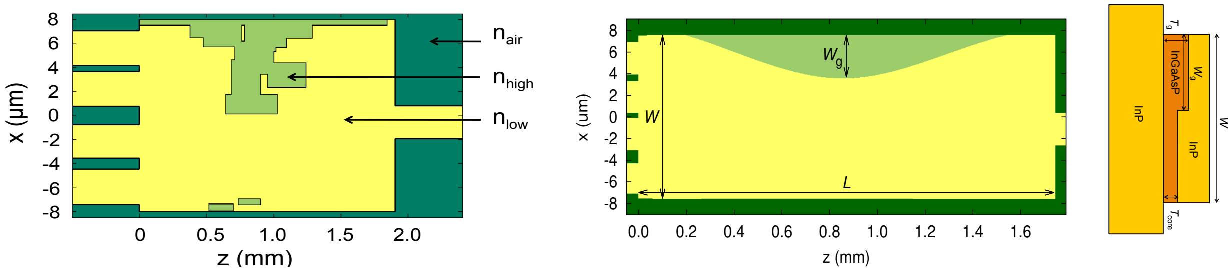
There are several approaches [8–11] to shorten the length of MMI couplers. In [8], Özbayat *et al.* reported non-uniform refractive index patterns with multiple rectangular patches. Non-straight sidewall MMIs using binomial functions [9], exponential functions [10], and parabolic functions [11], have been also studied to realize compact devices.

In this paper, we propose a spline-curved index step to design new compact MMI-based wavelength combiners. The simulation results show that an insertion loss close to 3 dB can be achieved with 1.74 mm device length for a 4×1 wavelength combiner. The proposed new wavelength combiner outperforms conventional power combiners by approximately 3 dB, and achieves even better performance in both transmittance and size than the rectangular-patch MMI [8]. Since it is straight and narrow, multiple devices can be placed densely, for various applications.

2. Spline-curved index-step MMI beam combiner

Fig. 1(a) shows an optimized MMI-based beam combiner reported in [8]. This device achieves 4.2 dB insertion loss at an MMI length of 1.9 mm for a wavelength spacing of 20 nm. This was realized by optimizing the sizes and locations of 16 rectangular patches having higher effective refractive index. Inspired by this rectangular-patch device, we propose the use of a spline-curved index-step region in an MMI beam combiner as illustrated in Fig. 1(b). The device is simplified to have two regions separated by a spline curve, one of whose sides has an InGaAsP core thickness of $T_{\rm core}$ and the other $T_{\rm g}$, as shown in Fig. 1(c), which depicts a cross-sectional view at the center of the MMI region. This difference of core thickness creates an effective refractive index step, which can potentially shorten the MMI wavelength combiner. The one-sided width $W_{\rm g}$ is characterized by a smooth spline curve, which is a piece-wise cubic polynomial function obtained by a few control points.

To design the spline-curved index-step MMI wavelength combiners, we use meta-heuristic optimization algorithms; more specifically, covariance matrix adaptation evolutionary strategy (CMA-ES) [12] for global search and Nelder-Mead [13] for local search considering fabrication tolerance [8]. We optimize the position of spline control points,



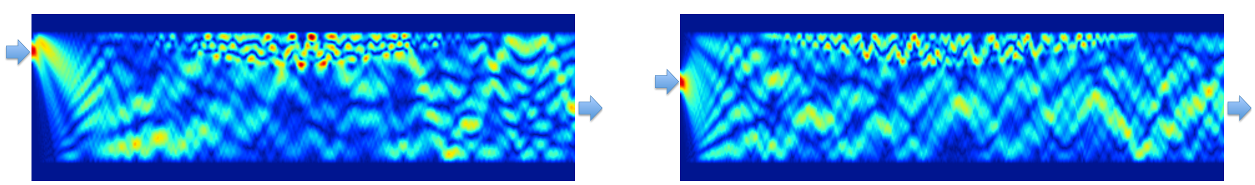
(a) Rectangular patch [8] (b) Spline-curved patch (c) Cross-section

Fig. 1. Compact MMI-based beam combiner with index step.

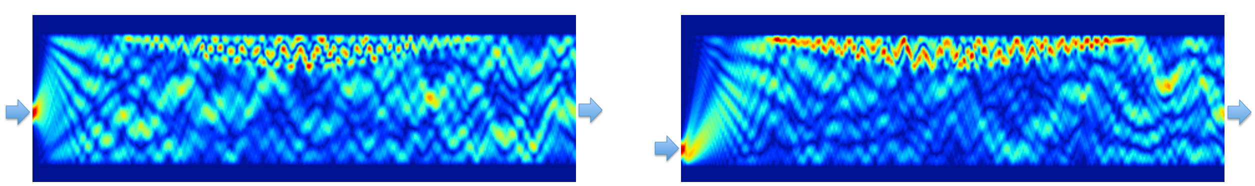
MMI width W, MMI length L, core thickness T_{core} and T_{g} under reasonable boundary conditions. The total number of optimization parameters is at least 21 for a 3-point spline case. During the optimization, we used 2-dimensional finite-difference beam propagation method (FD-BPM) with effective refractive index method [14]. Note that for an MMI-based 2-wavelength combiner, we proposed an initial device simulated with a 2D FD-BPM [8], and later obtained better performance with a refined structure [15] simulated with a 3D eigen-mode expansion (EME) method [16]. We plan to repeat the process in a similar manner.

We consider a 4.5 nm wavelength spacing for the standard [1], whose precise wavelengths are $\lambda_1 = 1295.56$, $\lambda_2 = 1300.05$, $\lambda_3 = 1304.58$, and $\lambda_4 = 1309.14$ nm. Fig. 1(b) shows the optimized device, whose length and width are $L = 1.74$ mm and $W = 15.1\,\mu$m for core thicknesses of $T_{\text{core}} = 0.25\,\mu$m and $T_{\text{g}} = 0.53\,\mu$m. This was the best case after 50 independent runs of CMA-ES, each of which iterates 1000 times for optimization loop. Here, the spline curve has $W_g = 3.96\,\mu$m at the center of the MMI region. As we will see below, the simplified and reduced-size structure with a spline curve improves the transmittance by 1 dB compared with the more complicated rectangular-patch MMI, which was designed for more relaxed conditions of 20 nm wavelength spacing.

3. Performance evaluations



(a) Port 1: wavelength $\lambda_4 = 1309.14$ nm (b) Port 2: wavelength $\lambda_1 = 1295.56$ nm



(c) Port 3: wavelength $\lambda_3 = 1304.58$ nm (d) Port 4: wavelength $\lambda_2 = 1300.05$ nm

Fig. 2. Propagation patterns of optimized 4-beam combiner with spline-curved index step.

Fig. 2 shows propagation patterns of the optimized device, where Figs. 2(a) through 2(d) correspond to the first to fourth input ports with different wavelengths of λ_4, λ_1, λ_3, and λ_2. It is observed that the propagation patterns are well designed to combine 4 beams into a single output port by means of the upper index-step region, which gradually interferes the modes in MMI. Note that the optimized port is not assigned in a natural order of wavelengths. From this result, we assume that the optimized wavelength combiner behaves as an MMI-MZI interleaver [17, 18] having AWG with specific arm lengths to create the phase difference, as depicted in Fig. 3. The insertion loss of the proposed device may come from an imperfect realization of the phase difference. Note that the length of an idealistic 4×4 MMI in Fig. 3 is 557 μm, which is almost exactly $1/3$ of the total length of the proposed wavelength combiner.

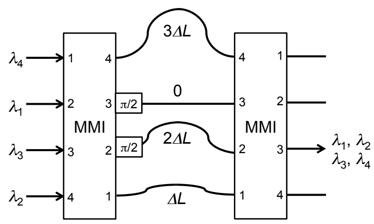
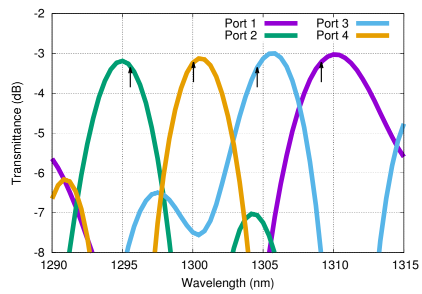
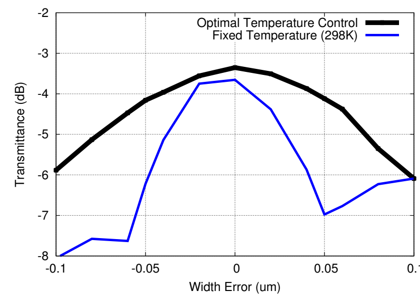


Fig. 3. Equivalent MMI model.



(a) Transmittance vs. wavelength



(b) Transmittance vs. width error

Fig. 4. Transmittance performance of optimized device.

Fig. 4(a) plots the transmittance curves at four ports as a function of wavelengths. The device achieves 3.35 dB insertion loss at the intended wavelengths (which are indicated by arrows). It should be noted that this transmittance performance is approximately 3 dB better than conventional MMI power combiners.

Fig. 4(b) shows the fabrication tolerance performance of the proposed wavelength combiner, with and without a thermal control. For a fabrication error of MMI width whithin $|\delta W| < 0.05\,\mu$m, the transmittance degradation is less than 0.7 dB. Since the fabrication error in the MMI width shifts the peak of transmittance curves from intended wavelengths, the conventionally used thermal control is needed to compensate for the loss.

4. Conclusions

We proposed a spline-curved index step to shorten wavelength combiners. A simulated insertion loss of near 3 dB was obtained for an InP-based 4-beam combiner of 1.74 mm long at a wavelength spacing of 4.5 nm. We showed that a blind optimization can design complex devices, and this technique is applicable to various types of optical devices.

References

1. 100GBASE-LR4/ER4 in IEEE 802.3ba.
2. S. Kanazawa, *et al.*, *IEEE Int'l Semiconductor Laser Conference* (2010) 57–58.
3. C. Yao, *et al.*, *Opt. Expr.* **20** (2012) 18248–18253.
4. J. Xiao, *et al.*, *Opt. Expr.* **15** (2007) 8300–8308.
5. Y. Barbarin, *et al.*, *IEEE PTL* **16** (2004) 2478–2480.
6. K. Watanabe, *et al.*, *Electron. Lett.* **47** (2011) 1245–1246.
7. F. Xia, *et al.*, *InP and Related Materials Conf.* (2006) 429–430.
8. S. Özbayat, *et al.*, *Opt. Commun.* **322** (2014) 131–136.
9. H.-C. Lu, W.-S. Wang, *IEEE JLT* **25** (2007) 2874–2878.
10. J.-J. Wu, '*Progress in Electromagnetics Research C* **1** (2008) 113–122.
11. P. P. Sahu, *Int'l Conf. on Design and Manufacturing* **64** (2013) 215–223.
12. M. D. Gregory, *et al.*, *IEEE Trans. Antennas Propag.*, **59** (2011) 1275–1285.
13. J. A. Nelder, R. Mead, *Computer J.* **7** (1965) 308–313.
14. R. G. Hunsperger, *Integrated Optics, 6th Ed.* Springer, 2009.
15. S. Siddharth, *et al.*, *Opt. Expr.* **22** (2014) 8533–8540.
16. T. P. Felici, D. F. G. Gallagher, *SPIE* **4986** (2003) 48–58.
17. C. van Dam, *et al.*, *Proc. 7th Eur. Conf. on Int. Opt.* (1995) 275 –278.
18. Y. Ueda, *et al.*, *Opt. Expr.* **22** (2014) 7844–7851.