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Zarin Tasnim Nijhum

Physics Discipline, Khulna University, Khulna-9208, Bangladesh

Nazmus Shakib Lalin

nazmusshakiblalin@gmail.com

Physics Discipline, Khulna University, Khulna-9208, Bangladesh <https://orcid.org/0009-0002-5460-0506>

Preangka Roy

Physics Discipline, Khulna University, Khulna-9208, Bangladesh

Shirazum Monira

Department of Electrical and Electronic Engineering, Bangladesh University of Engineering and Technology, Dhaka-1000, Bangladesh

Md. Sohel Sikder

Physics Discipline, Khulna University, Khulna-9208, Bangladesh

Md. Omar Faruk Rasel

Physics Discipline, Khulna University, Khulna-9208, Bangladesh <https://orcid.org/0000-0002-5729-6426>

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Optimization and Performance Analysis of 1×2 and 1×4 MMI Splitters on a Polymer Platform for Board-Level Optical Interconnects

ZARIN TASNIM NIJHUM,¹ NAZMUS SHAKIB LALIN,^{1,*} PREANGKA ROY,¹ SHIRAZUM MONIRA,² MD. SOHEL SIKDER,¹ AND MD. OMAR FARUK RASEL^{1,3}

¹Physics Discipline, Khulna University, Khulna-9208, Bangladesh

²Department of Electrical and Electronic Engineering, Bangladesh University of Engineering and Technology, Dhaka-1000, Bangladesh

³Department of Electrical and Computer Engineering, University of Delaware, Newark, DE 19716, USA

*nazmusshakiblal@gmail.com

Abstract: Polymer waveguides are promising for short-reach, board-level optical interconnects due to low-loss propagation and fabrication compatibility. This work presents the design, beam-propagation-method (BPM) simulation, and optimization of step-index polymer multimode-interference (MMI) splitters with 1×2 and 1×4 configurations at $\lambda = 1550$ nm. The devices are modeled in RSoft BeamPROP using SUNCONNECT organic–inorganic hybrid polymers (core: NP001L2, $n = 1.573$; cladding: NP216, $n = 1.560$). Geometrical parameters of the multimode section and access/output interfaces, including W_{MMI} , L_{MMI} , taper dimensions, and port spacing, are refined via parametric sweeps to obtain clean self-imaging with low loss and uniform splitting. The optimized 1×2 splitter achieves 50%/50% power splitting with excess loss of 0.137 dB (TE) and 0.139 dB (TM) and polarization-dependent loss of 0.002 dB. The optimized 1×4 splitter provides near-uniform splitting (25.07%, 24.93%, 24.93%, 25.07%) with excess loss of 0.333 dB (TE) and 0.344 dB (TM) and polarization-dependent loss of 0.011 dB. The total device lengths are $670 \mu\text{m}$ (1×2) and $1430 \mu\text{m}$ (1×4). These results indicate that compact polymer MMI splitters can provide low-cost, low-loss, and scalable passive fan-out for board-level optical routing.

1. Introduction

Electrical interconnects on printed circuit boards are approaching limits that cannot be relieved independently: aggregate bandwidth, energy per transmitted bit, and signal integrity degrade together as data rates rise [1–3]. Optical links break this coupling, and silicon photonics has established their viability at chip and package scale [4]. At board scale the binding constraint shifts from device performance to the cost of patterning waveguides over large areas, and this is where polymer platforms become attractive: they combine acceptable propagation loss with direct UV-lithographic processing on large-area and mechanically flexible substrates [5–7]. Within such a link a single source must typically feed several receivers, so a compact, low-loss passive fan-out element is required [8]. Multimode interference (MMI) devices meet this need by exploiting self-imaging in a wide multimode section [9, 10]: a single lithographic layer defines the entire component, the splitting ratio is set by geometry rather than by evanescent coupling, and the resulting tolerance to width and index variation is correspondingly looser than for directional couplers [11]. These properties have established MMI sections as a standard building block alongside the microring- and interferometer-based elements used in on-chip optical networks [12], and board-level demonstrations on polymer cores confirm that the platform supports error-free operation at interconnect scale [13].

Polymer MMI splitters on the SUNCONNECT platform have previously been studied for step- and graded-index cores [5] and in Y-branch layouts assisted by compact MMI sections [14, 15].

46 Four-way fan-out in polymer has so far been pursued mainly in three-dimensional geometries
 47 written by direct laser lithography [16, 17], which achieve very short interference sections but
 48 report substantial port-to-port imbalance. Those studies establish the platform and the two-way
 49 splitting function, but they do not address higher-order passive fan-out on a step-index polymer
 50 core, and they treat the self-imaging relations mainly as a qualitative starting point rather than
 51 as a quantitative sizing tool. The present work differs in three respects. First, it extends the
 52 step-index polymer platform from two-way to four-way fan-out at $\lambda = 1550$ nm within a footprint
 53 below 1.5 mm. Second, it applies the symmetric-interference relations—the appropriate imaging
 54 condition for a centrally excited $1 \times N$ splitter [9, 10]—as a quantitative sizing tool on this material
 55 system, and establishes where that approach holds and where it breaks down: once the multimode
 56 width is fixed by the geometric constraints of the output interface, the closed-form imaging length
 57 is shown to be quantitatively predictive for the 1×2 device, whereas the substantially larger
 58 discrepancy for the 1×4 device is traced to incomplete excitation of the high-order symmetric
 59 modes by a wide input taper, whose output pitch is correspondingly mirror-symmetric but not
 60 exactly equidistant. Third, it reports a full TE/TM performance set, including per-port insertion
 61 loss and polarization-dependent loss, for both configurations on a single material stack.

62 **2. Materials, Device Design, and Analytical Model**

63 *2.1. Material System and Platform Choice*

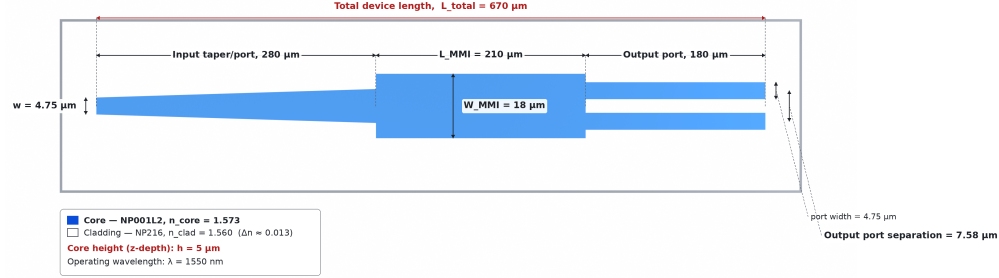
64 Organic–inorganic hybrid polymers from the SUNCONNECT series (Nissan Chemical Industries,
 65 Japan) were used for both core and cladding: NP001L2 as the core ($n_{\text{core}} = 1.573$) and NP216
 66 as the cladding ($n_{\text{clad}} = 1.560$), giving an index contrast $\Delta n = 0.013$ at $\lambda = 1550$ nm. These
 67 materials are thermally stable and compatible with standard UV-lithographic processing, which is
 68 what makes large-area patterning on optical printed circuit boards practical [7, 13]. A step-index
 69 (S.I.) profile was chosen because the index is uniform within the core and changes abruptly at the
 70 core–cladding boundary, yielding predictable mode confinement and stable phase evolution and
 71 hence high-fidelity self-imaging [9]. Graded-index profiles, by contrast, perturb the higher-order
 72 propagation constants nonlinearly and can disrupt the interference condition required for accurate
 73 imaging [5, 11], besides requiring more complex fabrication than UV-lithographic polymer
 74 processing. The same material stack is used for the access guides, tapers, multimode section, and
 75 output guides, which removes index mismatch and Fresnel reflection at the internal interfaces.
 76 This contrast is sufficient for a short beat length L_π , a compact footprint, and low modal leakage.

77 *2.2. Device Architecture*

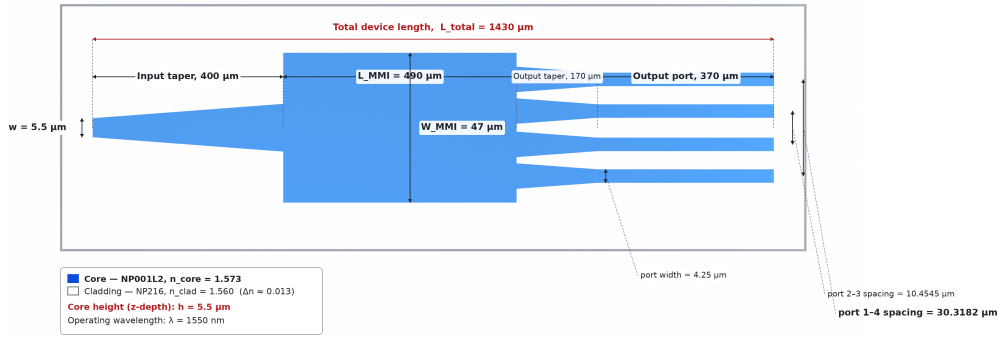
78 Each device comprises (i) a single access waveguide, centred on the device axis and operated in
 79 its fundamental lateral mode, (ii) a multimode section supporting several lateral modes, and (iii)
 80 N output waveguides placed at the self-image plane and likewise operated in the fundamental
 81 lateral mode. Linear/adiabatic tapers connect the access and output guides to the multimode
 82 section to improve mode matching and reduce transition loss. The cladding is a uniform NP216
 83 background enclosing the core, large compared with the mode field, and a single core height is
 84 used throughout each device. Figure 1 shows the plan-view layouts of both splitters; all labelled
 85 dimensions are the optimized values collected in Table 2.

86 Applying the effective-index method to the vertical stack, the fundamental slab mode of the
 87 $5\ \mu\text{m}$ (1×2) and $5.5\ \mu\text{m}$ (1×4) core gives lateral effective numerical apertures of 0.174 and
 88 0.177, so the lateral single-mode cut-off width $\lambda/2\text{NA}_{\text{eff}}$ is approximately $4.5\ \mu\text{m}$ and $4.4\ \mu\text{m}$.
 89 The chosen guide widths of $4.75\ \mu\text{m}$ and $5.5\ \mu\text{m}$ therefore lie modestly above cut-off, and each
 90 guide formally supports a second lateral mode. That mode is antisymmetric about the guide
 91 axis and sits close to cut-off, so it is only weakly confined; because both devices are excited
 92 and read out symmetrically about the device axis, its overlap with the launched and imaged

fields is negligible by parity, and the guides operate effectively in the fundamental lateral mode. The widths were retained rather than narrowed to strict single-mode values because narrowing would reduce the launched mode field and degrade the overlap with the MMI image lobes. Single-mode design practice on the SUNCONNECT family, where the reported lateral cut-off width depends strongly on the chosen core-cladding index pair, is discussed in [14, 18]; a direct modal decomposition at the output plane is left to experimental validation.



(a) 1×2 splitter



(b) 1×4 splitter

Fig. 1. Plan-view schematics of the optimized (a) 1×2 and (b) 1×4 MMI splitters, showing the central input taper, the multimode-interference section, and the output access waveguides embedded in the step-index polymer cladding. The longitudinal (propagation) axis is compressed relative to the transverse dimensions for display clarity; all labelled dimensions correspond exactly to the simulated devices and are listed in Table 2.

2.3. Self-Imaging Design Rules and Analytical Seeds

Self-imaging—the periodic reproduction of an input field at intervals along a multimode waveguide, produced by interference among guided modes of differing phase velocity—was established for planar waveguides by Bryngdahl [19] and Ulrich and Ankele [20], and was cast into the closed-form design relations used here by Soldano and Pennings [9] and Bachmann *et al.* [10]. We adopt those results directly rather than reproducing the modal derivation.

Three imaging mechanisms are conventionally distinguished, and they differ only in where the input field is launched across the multimode section [9, 10]. In *general interference* the input may be placed anywhere and N -fold images—that is, images consisting of N lobes, the integer m indexing successive image planes along z —form at $L = (m/N) 3L_\pi$. In *paired interference* the input is placed at $x = \pm W_c/6$, leaving the modes $v = 2, 5, 8, \dots$ unexcited, and images form at $L = (m/N)L_\pi$. In *symmetric interference* the input is centred on the multimode section,

only the even symmetric modes are excited, and images form at $L = (m/N)(3L_\pi/4)$, which shortens the device by a factor of four relative to general interference, independently of N . Both splitters reported here use a single centrally located access waveguide and therefore operate in the symmetric-interference regime. The distinction is not cosmetic: applying the general- or paired-interference relation to a centrally excited device mis-sizes the multimode section by factors of 4 and 4/3, respectively. Besse *et al.* further show that symmetric interference offers the widest optical bandwidth and the loosest fabrication tolerance for a given multimode width [21], which reinforces its selection here.

Following [9], the beat length of the two lowest-order lateral modes, with propagation constants β_0 and β_1 , is

$$L_\pi = \frac{\pi}{\beta_0 - \beta_1} \approx \frac{4 n_{\text{eff}} W_e^2}{3 \lambda}, \quad (1)$$

where λ is the free-space wavelength, n_{eff} is the effective index of the multimode slab, and W_e is the effective width including lateral field penetration,

$$W_e = W_{\text{MMI}} + \Delta W. \quad (2)$$

The corresponding symmetric-interference N -fold imaging length is [9]

$$L_{\text{MMI}} = \frac{m}{N} \left(\frac{3L_\pi}{4} \right), \quad m \in \mathbb{Z}^+, \quad (3)$$

with $N = 2$ for 1×2 and $N = 4$ for 1×4 . Throughout this work the first symmetric image ($m = 1$) is used.

For reproducibility we state the seeding procedure explicitly. Following the effective-index treatment of buried step-index guides [9, 11], the slab effective index is approximated by the arithmetic mean of the core and cladding indices,

$$n_{\text{eff}} \approx \frac{n_{\text{core}} + n_{\text{clad}}}{2}, \quad (4)$$

which is adopted only to seed the geometry; substituting n_{core} for n_{eff} in Eq. (1) changes the predicted imaging length by less than 0.5%, smaller than the deviation between the analytical prediction and the BPM optimum reported in Section 3. The lateral penetration of the guided field into the cladding, which arises from the Goos–Hänchen shift at the core–cladding interface, is accounted for through the width correction [9]

$$\Delta W = \frac{\lambda}{\pi} \left(\frac{n_{\text{clad}}}{n_{\text{core}}} \right)^{2\sigma} \frac{1}{\sqrt{n_{\text{core}}^2 - n_{\text{clad}}^2}}, \quad (5)$$

with $\sigma = 0$ for TE and $\sigma = 1$ for TM polarization [9]. For the present index pair this gives $\Delta W = 2.445 \mu\text{m}$ (TE) and $2.404 \mu\text{m}$ (TM); the 1.6% difference is negligible at the sizing stage, so the TE value is used for all analytical seeds. The output-guide centre positions for ideal overlap with the self-images, measured from the sidewall of the multimode section, are [9, 10]

$$x_k = \frac{(2k-1)}{2N} W_e, \quad k = 1, 2, \dots, N. \quad (6)$$

Equations (1)–(6) fix the multimode-section length and the output pitch once W_{MMI} is chosen; they do not by themselves prescribe W_{MMI} , which is instead bounded from below by the number of lateral modes needed to synthesize a clean N -fold image and by the physical separation required between output guides. BPM refinement is therefore used to select W_{MMI} and then to adjust L_{MMI} , taper lengths, and output pitch around the analytically predicted values so as to minimize imbalance and reduce insertion and excess loss, following established interface-design practice for polymer MMI splitters [5, 14, 15].

2.4. BPM Simulation Workflow and Pre-Optimization Screening

All structures were evaluated with the finite-difference beam-propagation method [22] as implemented in RSoft BeamPROP [23] at $\lambda = 1550$ nm. The workflow proceeded in three stages: (i) analytical estimation of W_{MMI} and L_{MMI} from Eqs. (1)–(6); (ii) parametric sweeps of widths, lengths, taper geometry, and port spacing; and (iii) selection of the final designs by minimizing excess loss and maximizing output-power uniformity. Final simulations for both devices were run in **full vector mode** on a fine transverse and longitudinal grid, so as to resolve polarization effects, mode coupling, and the detailed field variation across the multimode region, and thereby to make the predicted insertion loss, excess loss, and power splitting ratio reliable. All numerical post-processing and plotting were performed with Python scripts.

The analytical seeds of Table 1 follow from Eqs. (1)–(3) with $W_e = 14.445 \mu\text{m}$, $L_\pi = 281.16 \mu\text{m}$ for the 1×2 device and $W_e = 18.445 \mu\text{m}$, $L_\pi = 458.44 \mu\text{m}$ for the 1×4 . When implemented in BPM, they produced weak and imbalanced images at the intended planes, with high excess and insertion loss and significant deviation from uniform splitting. The cause is not a failure of the self-imaging relations but the choice of W_{MMI} that seeds them. At $W_{\text{MMI}} = 12 \mu\text{m}$ and $16 \mu\text{m}$ the multimode section supports too few lateral modes for a clean N -fold reconstruction, and the image positions predicted by Eq. (6) fall closer together than the physical width of the access waveguides, so the output guides cannot be placed on the image lobes without overlapping. Widening the multimode section is therefore a geometric necessity rather than an empirical correction, and it motivates the staged optimization of Section 3, in which W_{MMI} is first increased until the image lobes are physically resolvable and Eqs. (1)–(6) are then re-evaluated at the new width.

3. Optimization of the Devices

Both devices were optimized to minimize excess loss and to equalize the output powers. Starting from the analytical seeds, which as shown in Section 2.4 do not resolve the self-image lobes, a staged refinement was undertaken: **coarse sweeps** of W_{MMI} and L_{MMI} (step $5 \mu\text{m}$) to bracket the imaging regions; **fine sweeps** (step $0.25 \mu\text{m}$) around promising points; **taper-length tuning** to match the mode fields between the access guides and the multimode section; and **input/output offset adjustment** to align the output ports with the image maxima. For the four-port device, deliberately extending L_{MMI} beyond the target imaging plane was used as a diagnostic, since it reveals the full longitudinal range over which the four-lobe image forms and collapses and hence identifies the optimum output plane; uniformity was then recovered by adjusting the port spacing, which remains mirror-symmetric about the device axis but is not equidistant between adjacent ports.

Once W_{MMI} is fixed by the geometric constraints described above, the imaging length is not a free parameter. Re-evaluating Eqs. (1)–(3) at the optimized widths gives the predictions listed in Table 1, which are compared against the BPM optima below.

Table 1. Analytical seeds, symmetric-interference predictions re-evaluated at the optimized multimode width, and final BPM-optimized parameters.

Device	Analytical seed (μm)		At optimized width (μm)		
	W_{MMI}	L_{MMI}	W_{MMI}	L_{MMI} , Eq. (3)	L_{MMI} , BPM
1×2 splitter	12	105.44	18	211.22	210
1×4 splitter	16	85.96	47	617.70	490

3.1. Optimization of the 1×2 MMI Splitter

An **initial sweep** of W_{MMI} was performed first, since the multimode width sets both the number of guided lateral modes and the physical separation of the image lobes; increasing it improved confinement, improved the self-image quality, and reduced excess loss. The input taper was constructed with a starting vertex equal to the waveguide width and an ending vertex equal to twice the waveguide width. The two output guides were placed symmetrically about the device axis, each offset by $W_{\text{MMI}}/4.75 = 3.79 \mu\text{m}$, giving a centre-to-centre separation of $7.58 \mu\text{m}$. A **fine adjustment** of L_{MMI} then set the output symmetry. Iterative sweeps gave $W_{\text{MMI}} = 18 \mu\text{m}$ and $L_{\text{MMI}} = 210 \mu\text{m}$; the resulting field is shown in Fig. 2(a).

At $W_{\text{MMI}} = 18 \mu\text{m}$ the effective width is $W_e = 20.445 \mu\text{m}$, the multimode section supports approximately five guided lateral modes—estimated from the standard symmetric-slab relation $M \approx 2W_e \text{NA}/\lambda$, with $\text{NA} = \sqrt{n_{\text{core}}^2 - n_{\text{clad}}^2} = 0.202$ —and Eqs. (1) and (3) give $L_\pi = 563.25 \mu\text{m}$ and place the first-order symmetric image plane ($m = 1$), at which the field forms two lobes, at $L_{\text{MMI}} = 211.22 \mu\text{m}$. The BPM optimum of $210 \mu\text{m}$ deviates from this by only 0.58%. The self-imaging relations therefore remain quantitatively predictive on this polymer platform once the multimode width is set by the geometry of the output interface; the role of the numerical optimization is to fix W_{MMI} and the interface geometry, not to correct the imaging length. The transverse port placement is less tightly constrained: Eq. (6) locates the two image lobes at $\pm 5.11 \mu\text{m}$, whereas the optimum places the guides at $\pm 3.79 \mu\text{m}$. This is expected, because the two quantities are constrained by different physics. The imaging length fixes the relative modal phase and is therefore sharply defined, whereas the port position governs only the overlap integral with the image field; each of the two lobes occupies roughly half the multimode width, far broader than the $4.75 \mu\text{m}$ output guide, so coupling remains near-maximal over a wide range of transverse offsets.

3.2. Optimization of the 1×4 MMI Splitter

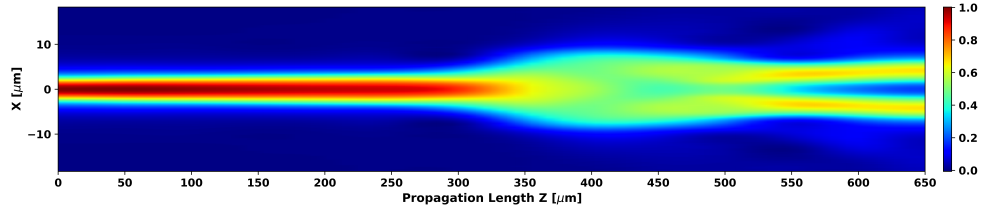
The 1×4 layout was derived by extending the unoptimized 1×2 design with two additional output ports, symmetrically placed, while preserving the single centred input. Simulations of that starting geometry showed markedly lower power in the outer ports, indicating insufficient lateral mode expansion for the original width. A **width sweep** was therefore carried out in successive steps. Enlarging the access-waveguide cross-section from $4.75 \times 5 \mu\text{m}^2$ to $5.5 \times 5.5 \mu\text{m}^2$ further improved the balance between inner and outer ports, because the broader launched field illuminates a larger fraction of the multimode section and so delivers more power to the outer image lobes. This gain in port balance is obtained at a cost in modal completeness: a broader, less divergent launch couples less strongly to the highest-order symmetric modes of the slab, which is the effect that displaces the optimum imaging plane from the closed-form prediction, as quantified below. **Taper vertex refinement**, with starting vertex $W_{\text{wg}}/1.75$ and ending vertex $2.5 W_{\text{wg}}$, produced a well-conditioned input field and a near-uniform output region within the first-fold image; tapering was also added at the output ports. At $W_{\text{MMI}} = 47 \mu\text{m}$, power delivery across all four ports became viable, though uniformity was still suboptimal.

A **length sweep** with the width fixed then tuned the imaging plane, the final value of $490 \mu\text{m}$ giving a splitting variation below 0.2% between ports. Finally, **port geometry and spacing** were refined: output tapers of $170 \mu\text{m}$ and reduced port widths of $4.25 \mu\text{m}$ improved coupling efficiency, while the outer and inner port separations were set to $30.3182 \mu\text{m}$ and $10.4545 \mu\text{m}$, respectively. The resulting field is shown in Fig. 2(b).

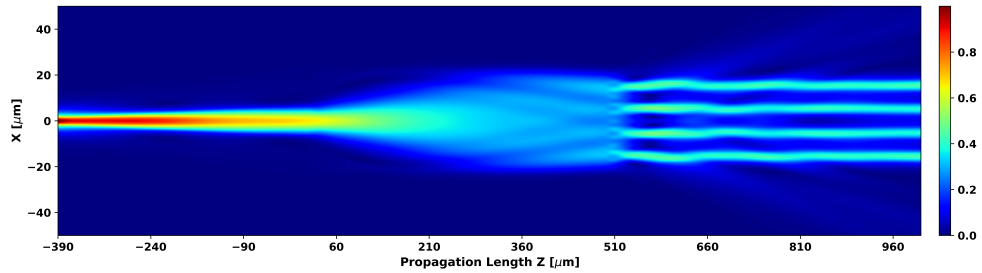
Agreement with the closed-form model is looser here than for the 1×2 . At $W_{\text{MMI}} = 47 \mu\text{m}$ the effective width is $W_e = 49.445 \mu\text{m}$, the multimode section supports approximately thirteen guided lateral modes by the same estimate, and Eqs. (1) and (3) predict $L_\pi = 3294.41 \mu\text{m}$ and place the first-order symmetric image plane ($m = 1$), at which the field forms four lobes, at

$L_{\text{MMI}} = 617.70 \mu\text{m}$, whereas the BPM optimum is $490 \mu\text{m}$, i.e. 20.7% shorter. The optimized output positions deviate with the same sign: Eq. (6) places the four image lobes at $\pm 6.18 \mu\text{m}$ and $\pm 18.54 \mu\text{m}$ from the device axis, while the BPM optimum places the ports at $\pm 5.23 \mu\text{m}$ and $\pm 15.16 \mu\text{m}$, i.e. 15–18% further inboard. Both deviations are consistent with an effective imaging aperture narrower than the physical slab. The 1×4 device is fed through a wide input taper whose end face spans $13.75 \mu\text{m}$ into a $47 \mu\text{m}$ slab: this is the deliberate trade-off noted above, in that the broad launch is what fills the outer image lobes and secures port balance, but being broad and of low divergence it couples only weakly to the highest-order symmetric modes, and truncating the modal expansion in this way both shortens the apparent beat length and contracts the transverse image spacing. The closed-form model, which assumes that all symmetric modes of the full width W_e are excited, therefore overestimates both quantities for the 1×4 layout while remaining accurate for the more weakly multimoded 1×2 device.

The resulting pitch is mirror-symmetric but not exactly equidistant. Departures from the equidistant image positions of ideal symmetric interference are an established degree of freedom in MMI design, and the relation between coupler geometry and image intensity, position, and phase has been treated analytically for both uniform and non-uniform splitting [24]. Comparable three-dimensional polymer 1×4 splitters report markedly larger port-to-port imbalance [16, 17].



(a) 1×2 MMI splitter



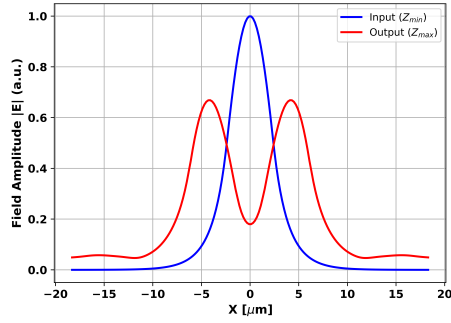
(b) 1×4 MMI splitter

Fig. 2. Simulated field-intensity contour maps of the optimized splitters at $\lambda = 1550 \text{ nm}$: (a) the 1×2 device, showing the two-fold self-image with uniform power distribution, and (b) the 1×4 device, showing the four-fold self-image with balanced power across all four ports.

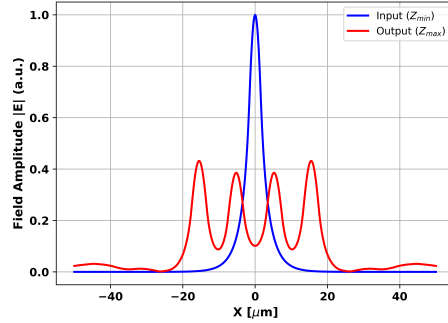
4. Performance Analysis and Evaluation

4.1. Field Amplitude Distribution and Power Splitting Ratio

The transverse field amplitude was extracted from the BPM data at the input and output planes of both devices, and is shown in Fig. 3. The two outputs of the 1×2 device are essentially identical, while the 1×4 device shows a slight asymmetry between ports of approximately 0.05 a.u.



(a) 1×2 MMI splitter



(b) 1×4 MMI splitter

Fig. 3. Field amplitude distribution at the input and output planes of the designed MMI splitters: (a) 1 × 2 splitter and (b) 1 × 4 splitter.

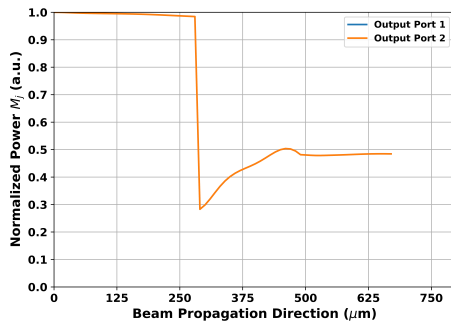
Because these devices are intended as power splitters, the uniformity of the output distribution is the primary figure of merit. The power splitting ratio at the i -th port is

$$\text{PSR}_i = \frac{P_{\text{out},i}}{\sum_{j=1}^N P_{\text{out},j}} \times 100\%, \quad (7)$$

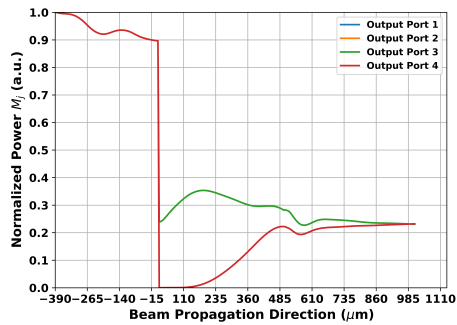
where $P_{\text{out},i}$ is the optical power at the i -th output port; for an ideal N -port splitter $\text{PSR}_i = 100/N\%$ for all ports [25]. The splitting ratio of an MMI device is set by its geometry, and deliberate departures from the symmetric layout can be used to realize arbitrary ratios [26]. The values obtained from Eq. (7) for both devices are listed in Table 2.

4.2. Power Evolution Along the Device

Figure 4 follows the normalized power in each output channel from the input to the output facet, tracking the self-imaging behaviour through the multimode section at 1550 nm. In Fig. 4(a) a single trace is visible because ports 1 and 2 carry identical power and their curves overlap; the uniform splitting ratio is established at the exit of the multimode section, at $z = 490 \mu\text{m}$, as expected from self-imaging.



(a) 1×2 MMI splitter



(b) 1×4 MMI splitter

Fig. 4. Normalized power evolution along the beam propagation direction: (a) 1 × 2 MMI splitter and (b) 1 × 4 MMI splitter.

For the 1×4 device, Fig. 4(b) shows that beyond the exit of the multimode section at $z = 890 \mu\text{m}$ the channel powers continue to change slightly before converging to nearly equal values at the

266 output facet. This residual variation is attributable to small phase errors and mode mismatch at
 267 the multimode-to-output transition. It could be reduced by further optimizing the output port
 268 spacing and tapering, but increasing the separation would require a wider multimode section and
 269 a corresponding length adjustment, enlarging the footprint; graded-index profiles or lower-loss
 270 material platforms offer alternative routes.

271 4.3. Excess Loss, Insertion Loss, and Polarization-Dependent Loss

272 Three loss metrics characterize an $M \times N$ MMI splitter. All three were evaluated from the
 273 same BPM field-amplitude data used in Section 4.1, integrated over each port aperture at every
 274 propagation step, and are therefore internally consistent with the splitting ratios reported there.

275 *Excess loss* (EL) is the device-level measure of total power efficiency [9]:

$$EL = -10 \log_{10} \left(\frac{\sum_{j=1}^N P_{j,\text{out}}}{\sum_{i=1}^M P_{i,\text{in}}} \right) \text{ dB}, \quad (8)$$

276 where $\sum_j P_{j,\text{out}}$ is the summed power at all output ports and $\sum_i P_{i,\text{in}}$ the summed power at the
 277 inputs. An ideal splitter without internal loss gives $EL = 0$ dB, so any positive value represents
 278 power lost to scattering, absorption, radiation leakage, or mode mismatch inside the device.

279 *Insertion loss* (IL) is defined per output port and describes how the input power is distributed
 280 among the channels [9]:

$$IL_j = -10 \log_{10} \left(\frac{P_{j,\text{out}}}{\sum_{i=1}^M P_{i,\text{in}}} \right) \text{ dB}, \quad (9)$$

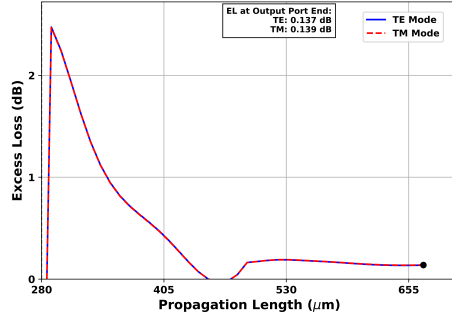
281 where $P_{j,\text{out}}$ is the power at the j -th output port and $\sum_i P_{i,\text{in}}$ the total launched power. For a
 282 lossless splitter IL_j reduces to the ideal splitting penalty $10 \log_{10} N$.

283 *Polarization-dependent loss* (PDL) is the difference between the excess losses of the two
 284 polarizations:

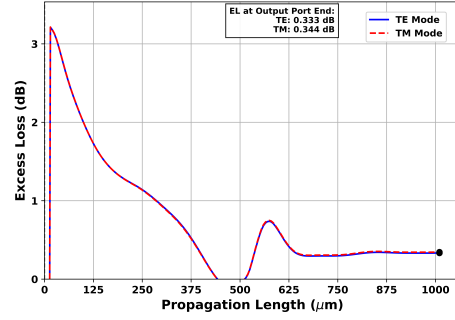
$$P_\alpha = |EL_{\text{TE}} - EL_{\text{TM}}|. \quad (10)$$

285 In the present model the polarization dependence originates in the vectorial asymmetry of the
 286 non-circular core cross-section: the E_x - and E_y -dominant modes satisfy different boundary
 287 conditions at the lateral and vertical core-cladding interfaces, and the resulting difference in
 288 lateral field penetration is captured by the Goos-Hänchen term of Eq. (5), where $\sigma = 0$ for
 289 TE and $\sigma = 1$ for TM give effective widths differing by 1.6% and hence slightly different
 290 beat lengths and imaging conditions for the two polarizations. Low polarization sensitivity is
 291 a recognized advantage of MMI splitters realized in polymer, where the core-cladding index
 292 contrast is modest [27]; conversely, strongly confining platforms can be engineered for deliberate
 293 polarization selectivity [28].

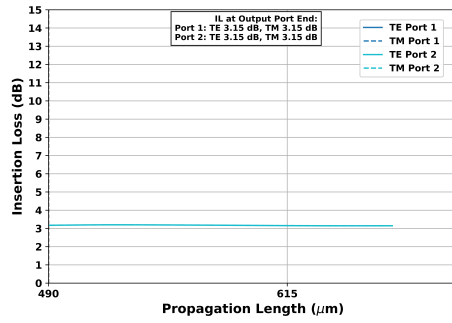
294 Figure 5 plots EL and IL against propagation length for both devices and both polarizations.
 295 The end-of-device values, together with the PDL obtained from Eq. (10), are collected in Table 2
 296 and are discussed in Section 4.4.



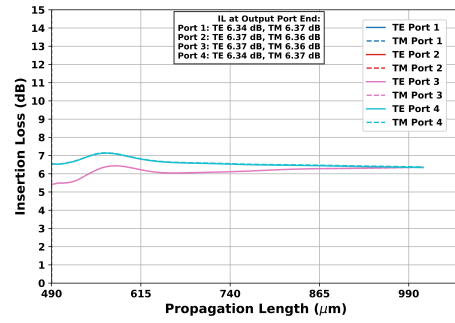
(a) Excess loss, 1×2 splitter



(b) Excess loss, 1×4 splitter



(c) Insertion loss per port, 1×2 splitter



(d) Insertion loss per port, 1×4 splitter

Fig. 5. Excess loss and insertion loss of the designed MMI splitters along the beam propagation direction for TE and TM polarization: (a) excess loss, 1×2 ; (b) excess loss, 1×4 ; (c) insertion loss of each output port, 1×2 ; (d) insertion loss of each output port, 1×4 .

Figures 5(a) and (b) show apparently negative excess loss over roughly 405–530 μm and 430–500 μm , respectively, i.e. a total output power exceeding the input. This is not physical amplification but a numerical artefact of the one-way, slowly-varying-envelope BPM formulation on a discretized transverse grid, whose approximate treatment of evanescent and backward-travelling components departs slightly from exact power conservation at abrupt transverse index steps; the limitation persists even when the paraxial restriction is relaxed in wide-angle schemes [29]. This occurs only within the multimode section, are taken as zero in the analysis and do not affect the end-of-device values.

4.4. Consolidated Performance Summary

Table 2 collects the optimized geometry and the complete computed performance set for both devices on a single material stack. Scaling from $N = 2$ to $N = 4$ increases the multimode width by a factor of 2.6 and the total device length by a factor of 2.1, and roughly doubles the excess loss, while the insertion loss per port remains within 0.35 dB of the ideal splitting penalty $10 \log_{10} N$ in both cases and the polarization-dependent loss stays below 0.02 dB.

Two complementary uniformity measures are reported. The *splitting non-uniformity* is the spread of the port-level PSR about $100/N\%$, expressed in percentage points. The *output power imbalance* is the difference between the largest and smallest per-port insertion loss, $\text{IL}_{\text{max}} - \text{IL}_{\text{min}}$, evaluated from the unrounded output powers. An imbalance below 0.05 dB is well within the margin required for passive fan-out in board-level links, where downstream receivers must in any

316 case accommodate several tenths of a decibel of channel-to-channel variation.

Table 2. Consolidated geometry and performance summary of the optimized polymer MMI splitters at $\lambda = 1550$ nm. All loss and splitting values are obtained from the BPM field-amplitude data as described in Sections 4.1 and 4.3.

Parameter	1×2	1×4
<i>Material and geometry</i>		
Core / cladding index	1.573 / 1.560	1.573 / 1.560
Index contrast Δn	0.013	0.013
MMI width W_{MMI} (μm)	18	47
MMI length L_{MMI} (μm)	210	490
Input taper / port length (μm)	280	400
Output taper length (μm)	—	170
Output port length (μm)	180	370
Access waveguide width (μm)	4.75	5.5
Core height, all segments (μm)	5	5.5
Output port width (μm)	4.75	4.25
Output port offset from axis (μm)	± 3.79	$\pm 5.23, \pm 15.16$
Output port separation, inner (μm)	7.58	10.4545
Output port separation, outer (μm)	—	30.3182
Total device length (μm)	670	1430
Guided lateral modes in MMI (approx.)	5	13
<i>Performance Metrics</i>		
PSR per port (%)	50.0 / 50.0	25.07 / 24.93 / 24.93 / 25.07
Splitting non-uniformity (pp)	0	0.07
Excess loss, TE (dB)	0.137	0.333
Excess loss, TM (dB)	0.139	0.344
Insertion loss, TE (dB)	3.15 / 3.15	6.34 / 6.37 / 6.37 / 6.34
Insertion loss, TM (dB)	3.15 / 3.15	6.37 / 6.36 / 6.36 / 6.37
Ideal splitting penalty $10 \log_{10} N$ (dB)	3.01	6.02
Output power imbalance, TE (dB)	0.00	0.03
Output power imbalance, TM (dB)	0.00	0.02
Polarization-dependent loss (dB)	0.002	0.011

317 5. Conclusion

318 This work presented the design, BPM simulation, optimization, and performance evaluation
 319 of polymer step-index MMI splitters in 1×2 and 1×4 configurations for board-level optical

interconnects. By tuning W_{MMI} , L_{MMI} , taper geometry, and port spacing, both devices achieved compact layouts (total lengths of $670\text{ }\mu\text{m}$ and $1430\text{ }\mu\text{m}$) with near-uniform splitting, excess loss below 0.35 dB, and polarization-dependent loss below 0.02 dB, as summarized in Table 2. A further result is methodological: once the multimode width is fixed by the geometry of the output interface, the symmetric-interference relations predict the optimized imaging length of the 1×2 device to within 0.6%, while the 20.7% shortfall for the 1×4 device is attributable to incomplete excitation of the highest-order symmetric modes by the wide input taper—the same broad launch that secures port balance. These splitters are therefore suitable for passive power distribution and fan-out in short-reach board-level optical links.

The results are based on BPM simulations under idealized conditions; fabrication variability and thermal and wavelength dependence were not evaluated. Analytical treatments indicate that symmetric-interference imaging is the most forgiving of the three regimes in both optical bandwidth and dimensional tolerance [21], so favourable margins are expected, but this remains to be quantified for the present geometry. Future work will address fabrication and experimental validation, followed by tolerance and thermal/wavelength characterization to establish practical operating margins.

Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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