Tapping Light From Waveguides by High-Order Mode Excitation and Demultiplexing

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***Abstract*—A novel high-performance optical tap with low wavelength-dependent loss (WDL), polarization-dependent loss (PDL), and excess loss is described. The tap is based on exciting a high-order mode by an abrupt change in the waveguide profile, and then tapping the optical power in the high-order mode by using a modal-demultiplexer. The tap can be designed to give a tapping ratio in the range of -30 to -10 dB over a wavelength range of 1510–1640 nm. In addition, it is shown that the tapping ratio is tolerant to process variations, repeatable and predictable, enabling the design to be implemented in a single process run, with no need for additional fine-tuning iterations, while achieving a high process yield. We show that measurements are in good agreement with simulated results. In the tap channel we measured 0.3 dB WDL and 0.2-dB PDL over the C- and L- bands, while the signal in the main channel was virtually uncontaminated relative to a plain single-mode reference waveguide.**

***Index Terms*—Mode-multiplexing, optical tap, planar lightwave circuits.**

I. INTRODUCTION

INTEGRATED optical circuits often require a method for monitoring the optical signal in various channels [1]. For example, power monitors are used for feedback in variable optical attenuators [2] and lasers [3]. The ideal optical signal monitor should have low wavelength-dependent loss (WDL) and polarization-dependent loss (PDL) and should not introduce these to the signal being monitored. In addition, to minimize the insertion loss, there should be minimal loss in excess of the power being tapped. One method for monitoring the signal in a waveguide consists of transferring a small portion of the signal to an adjacent waveguide (i.e., tapping the main waveguide), and then routing the tap waveguide to a detector at the chip facet or embedded in the chip itself [4]. In many cases, the required tapping ratio is in the order of a few percent, resulting from a compromise between minimizing the insertion loss and achieving an acceptable signal-to-noise ratio at the detector.

Conventional tap designs are based on directional couplers [3], or tapping waveguides at an angle to the main waveguide—such as a small angle cross or Y-branch [2]. The directional coupler is designed with a low coupling constant and suffers from strong wavelength dependence. Scalar beam propagation method (BPM) simulations for a conventional directional coupler[1] designed with a nominal tapping ratio of 3% at $\lambda = 1.55$ μm indicate that WDL is 5 dB in the wavelength range of $\lambda =$1500–1650 nm. In addition, the device is sensitive to deviations in the coupler gap in the order of ≈ 5 dB/μm. Therefore, it is usually required to empirically fine-tune the coupling constant to the desired level in an iterative manner by adding test devices with slight variations on the nominal geometry of the coupler, and correcting the design based on measurements of these test devices. This is also required when transferring the design to a different manufacturing process, or if process parameters are modified. Taps based on waveguides intersecting the main waveguide at an angle usually have a tapping ratio that is more predictable, but they too suffer from WDL, PDL, and relatively high excess loss.[2]

Newer tap designs are based on multistage directional couplers in a cascaded Mach–Zehnder interferometer (MZI) configuration or multiple-mode interference (MMI) couplers. The two-stage MZI coupler reported in [5] exhibits low WDL over a wide spectral range and a tapping ratio tuning range of 5%–50%. However, achieving broadband performance requires tight manufacturing tolerances that ensure a phase delay accurate to 1 part in 60, and the optimization algorithm for the design is rather complicated. A recent application [6] uses a three-stage MZI coupler tuned to a 5% tapping ratio with PDL <0.3 dB. Conventional MMI couplers may also be used for tapping optical signals in waveguides. These compact devices are considered robust, with low polarization and wavelength dependence, and have relatively large tolerance to manufacturing errors [7]. Their main drawback is that the coupling is limited to discrete ratios based on the self-imaging principle, but the design can be modified to allow a free selection of the coupling ratio [8].

Here we present a method for tapping the signal from the main waveguide, which fulfills the above requirements for low WDL, PDL, and excess loss. This design can also tolerate wide process variations, and the tapping ratio exactly matches the simulation results, so that the design can be implemented in a

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[1] We considered a directional coupler with $\Delta n = 0.75\%$, 6×6 μm^2 rectangular waveguides, a gap of 6 μm, and coupling length of 520 μm.

[2] We have measured cross-based taps and found WDL of 0.3 dB in the spectral range of 1530–1570 nm, and maximal PDL of 0.4 dB in the same range. Note that the WDL and PDL were present both in the tap channel and in the main channel.

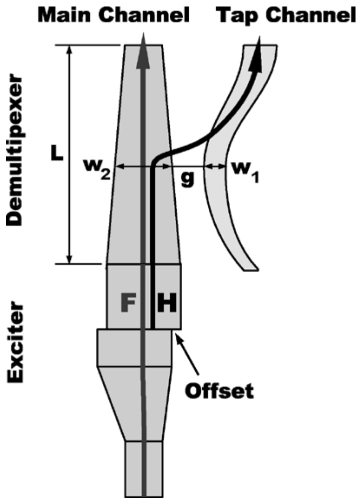


Fig. 1. Adiabatic mode-demultiplexer-based tap. Light enters the main channel in the fundamental mode of a single-mode waveguide. The waveguide adiabatically tapers to a double-mode waveguide such that only the fundamental mode is occupied. The small offset in the double-mode waveguide excites the high-order mode to the desired tapping ratio. Light continues propagating in the double-mode waveguide, with most of the power in the fundamental mode (F), a small part in the excited high-order mode (H), and a very slight portion is lost to the radiating modes. Both modes propagate in the multimode waveguide to the demultiplexer where the modes are spatially separated to the main channel and the tapping channel. The demultiplexer's main parameters are its length L, and the widths of the waveguides w_1 and w_2 at the minimal gap g.

single process run, with no fine-tuning, and with a high process yield. The devices described in [3]–[8] rely on interference effects between the main channel and tap channel, thereby increasing the risk of contaminating the signal in the main channel. On the other hand, the device presented here does not involve interference effects, so that the signal in the main channel is not degraded, and any PDL or WDL incurred by the device is present *only in the tap channel*. This is a very important consideration when the device is integrated into a large photonic circuit where the deficiencies of different circuit elements contribute to the overall WDL and PDL, and we believe that this aspect of the design is a crucial asset when compared to other types of optical taps.

II. DESIGN

In concept, our design is similar to that presented in [9], but as will be described, our implementation is different, employing a novel device, the adiabatic mode-demultiplexer [10], [11]. In both designs, the tap consists of two functional stages (Fig. 1). The first is the exciter stage, where a high-order mode is excited in the main waveguide. The second is the modal-demultiplexing stage, where the light occupying the high-order mode is fully transfered to an adjacent waveguide. The exciter stage determines the ratio between the high-order mode and the fundamental mode, and hence the tapping ratio.

Light propagating in the fundamental mode (generally of a single-mode waveguide) enters the high-order mode exciter stage, where a portion of the light is converted to a high-order mode. Since only a small fraction of the light (in the order of a few percent) is required to undergo mode conversion, the high-order mode is excited by an abrupt change in the local modal basis [9], [12].

Most typically, mode conversion is from the symmetric fundamental mode to the first-order antisymmetric mode, and this is facilitated by an abrupt lateral offset in a multimode waveguide capable of supporting two modes (note that since the signal to be tapped is usually in a single-mode waveguide, the offset in the mode exciter is preceded by an adiabatic taper from the single-mode waveguide to the double-mode waveguide). The abrupt change in the modal basis causes the fundamental mode of the modal basis before the offset to slightly overlap with the first excited mode of the modal basis after the offset. We denote the modal basis before the offset by $\{\psi_i\}_{i=0,1}$ and after the offset by $\{\phi_i\}_{i=0,1}$. The slight change in modal basis can be written as

$$\psi_0 = A_0\phi_0 + A_1\phi_1 + \Delta. \tag{1}$$

Here, $|A_1|^2$ is the power in the excited mode (the tapping ratio), $|A_0|^2$ is the light remaining in the fundamental mode, and Δ is the light uncoupled to the double-mode waveguide. Thus, $\langle\Delta|\Delta\rangle$ is the lost power. For a slight offset where $|A_1|^2$ is in the order of a few percent, $|A_0|^2+|A_1|^2 > 0.99$, i.e., the lost power is less than 1.0%.

The abrupt change in the waveguide profile at the offset may cause unwanted back-reflections. Since the design was implemented in a $\Delta n = 0.75\%$ low index contrast core, the back-reflection for such an offset is less than -50 dB. Should, however, back-reflection pose a problem in a critical aplication or with a higher index contrast, [9] shows how to diminish the effect by adding a short tapered section at the offset. Basically, the taper length is chosen so that it is longer than the beat length between the counterpropagating modes and shorter than the beat length between the copropagating fundamental and first-order excited modes. Since the first beat length is in the order of 1 μm, while the second beat length is several hundered microns long, a taper length in the order of 10–20-μm-long functions as a discontinuity for the forward-propagating modes and as an adiabatic transition for the counterpropagating modes.

After excitation, light in both modes propagate in the double-mode waveguide to the next stage—mode-demultiplexing. The modal demultiplexer is a device for spatially separating light propagating in a multimode waveguide, based on the demultiplexing criterion which is mode order. The two conventional methods for achieving this functionality are the asymmetrical directional coupler [13], [14] and the asymmetric Y-branch [15]–[17]. The device described in [9] uses an asymmetric Y-branch as the mode demultiplexer. Our novel approach is the adiabatic mode demultiplexer, which exhibits extremely low WDL and PDL and is highly robust to process induced variations. Although a full description of the device is given in [10] and [11], a brief description is given here in order to more fully appreciate the inherent benefits of the design.

The demultiplexer consists of a double-mode waveguide adiabatically coupled to a single-mode waveguide, based on the avoided level-crossing principle [18]. The device starts with two waveguides, far enough apart to be virtually uncoupled. One waveguide supports two modes, while the other is a single-mode waveguide. The initial widths of the waveguides are chosen so that the high-order mode of the double-mode waveguide

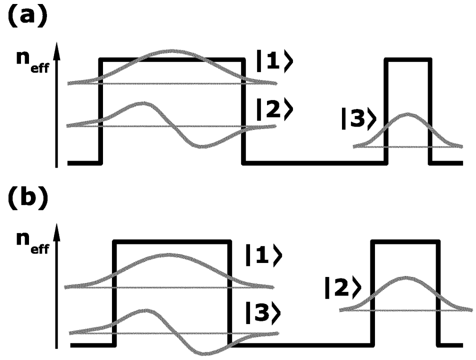


Fig. 2. Adiabatic mode-demultiplexer-mode effective index diagrams. (a) Initial effective index configuration at the beginning of the device. The first-order excited mode $|2\rangle$ is in the double-mode waveguide, while the second-order excited mode $|3\rangle$ is in the single-mode waveguide. (b) Final effective index configuration at the end of the device. Here, the high-order modes have switched waveguides, whereas the fundamental mode $|1\rangle$ remains in place.

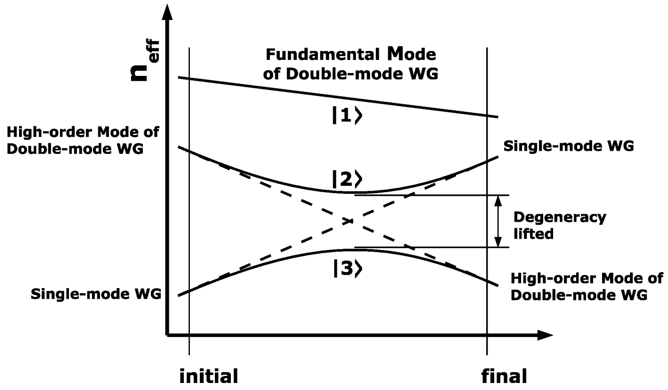


Fig. 3. Adiabatic mode-demultiplexer-mode effective index evolution. The horizontal axis denotes the position along the length of the device, from the initial configuration at the start of the device, to the final configuration at its end. The dashed line depicts the effective index evolution for uncoupled waveguides. The solid line shows the effective index evolution when coupling is introduced and degeneracy at the crossing point is lifted, thus achieving an avoided crossing. With the avoided crossing, mode $|1\rangle$ remains in the double-mode waveguide, modes $|2\rangle$ and $|3\rangle$ exchange waveguides.

has an effective index that is higher than the effective index of the mode in the single-mode waveguide (Fig. 2). At the end of the device, the double-mode waveguide is narrower while the single-mode waveguide is wider. This results in that the effective index of the high-order mode of the double-mode waveguide being lower than the effective index of the mode in the single-mode waveguide.

Along the length of the device, the initial modal basis is adiabatically evolved to the final modal basis, i.e., the double-mode waveguide is tapered to its narrower final width, and the single-mode waveguide has a taper that increases in width. If we were to do this while leaving the waveguides far apart and uncoupled, then there would be no power transfer between the waveguides, and the evolution of the modes' effective indexes would be as depicted by the dashed line in Fig. 3. Note that in the central region of the device the two excited modes' effective indexes cross, and these modes are degenerate. If, however, we would decrease the distance between the waveguides in the central region of the device, we would introduce coupling between the waveguides, and by second-order perturbation theory the degeneracy at the crossing point would be lifted. This is an example of an avoided-crossing, as can be seen in the solid line in Fig. 3. The adiabatic evolution in conjunction with the avoided crossing define the devices demultiplexing functionality—the fundamental mode of the double-mode waveguide remains in place, and the high-order mode of the double-mode waveguide is adiabatically transfered to the single-mode waveguide.

Being adiabatic, this device has virtually no polarization or wavelength dependence. Also note that if the device is not perfectly adiabatic, only the signal in the high-order mode that is deflected to the single-mode waveguide is affected, and the main signal in the fundamental mode channel is not influenced [11]. The adiabaticity of the device is a function of the length of the device and the level splitting at the crossing point. Obviously, as the device is scaled to be longer, the adiabaticity improves and the dependence on polarization and wavelength decrease. On the other hand, increasing the level splitting also improves the adiabaticity of the device. The level splitting is controlled by two parameters, the minimal gap g, and the waveguide widths at the minimal gap point w_1 and w_2 (Fig. 1). Decreasing the minimal gap increases the level splitting and improves the adiabaticity. Decreasing the waveguide widths w_1, w_2 serves to decrease mode confinement, thus strengthening the interaction between the waveguides and increasing the level splitting. Using these guidelines it is possible to tailor the polarization and wavelength dependence of the demultiplexer to an acceptable level, while meeting waveguide design rules dictated by process considerations.

III. SAMPLE AND EXPERIMENT

The design was implemented in a silica-on-silicon planar lightwave circuit (PLC). Rectangular waveguides were fabricated in a PECVD process with a germanium doped core of 6 μm height and $\Delta n = 0.75\%$ index contrast. The chip contained two series of tap devices, the first with a scan on the taps' mode exciter offset to check the tapping ratio's dynamic range, and the second with four identical taps with an offset of 1.1 μm to check consistency and repeatability. Refering to Fig. 1, the demultiplexers in the taps had the following parameters. The total length was $L = 6000$ μm. Width of the double-mode input waveguide was 12 μm, and the output single-mode waveguides were 6 μm wide. The waveguides at the critical minimal gap region had dimensions of $w_1 = 2.9$ μm, $w_2 = 9.2$ μm, and the gap was 4 μm wide. Rectangular 6×6 μm^2 single-mode waveguides were located in parallel and in close proximity to the test devices for reference purposes.

The experimental setup consisted of a continuous-wave external-cavity tunable fiber-coupled laser, a deterministic polarization controller, a bare-end fiber on an alignment stage to couple the light into the chip, and another bare-end fiber for coupling the light out of the chip and into a detector. The laser wavelength range was 1510–1640 nm, the optical power was 3 dBm (2 mW) for single-wavelength measurements, and -4.5 dBm (0.3 mW) for swept-wavelength measurements. The polarization controller was used for four-state measurement following the Mueller matrix method [19], yielding average transmission and PDL at the same measurement. Measurements

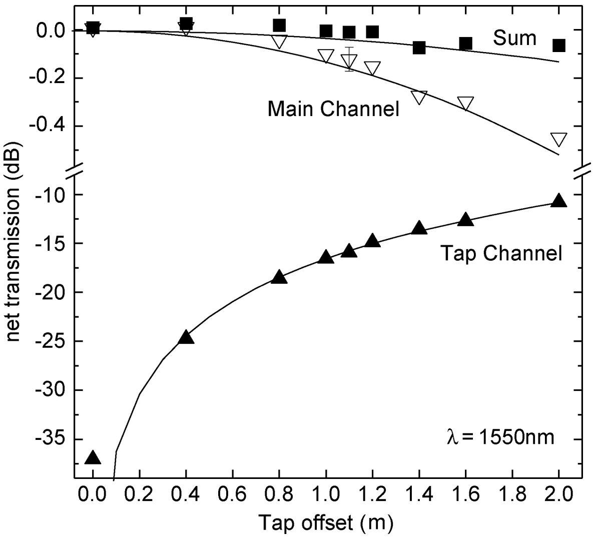


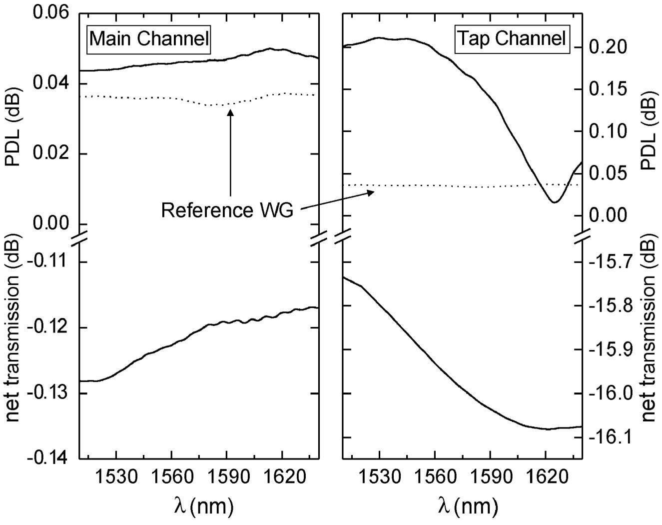
Fig. 4. Tapping ratio tuning. Net measured transmission (normalized to reference waveguides-symbols), and scalar BPM simulations (solid lines), at a wavelength of 1550 nm, for a series of devices with different offsets. Measurements were performed for the main channel and the tap channel and averaged over all polarizations. The "Sum" series is the sum of optical power in the tap channel and the main channel.

were performed at room temperature, with the chip temperature stabilized at 24 °C.

IV. RESULTS

The first experiment consists of nine taps with offsets varying in the range of 0–2 μm. The average insertion loss over all polarizations was measured in the main waveguide channel, in the tap channel, and in reference waveguides using the Mueller matrix technique, at a fixed wavelength of 1550 nm. The insertion loss of the reference waveguide was -0.9 dB, dominated by the loss due to mode mismatch at the fiber-chip interfaces. The insertion loss of the reference waveguide was subtracted from the device transmission to yield the net tap transmission,[3] shown as symbols in Fig. 4. The series denoted by "Sum" is the sum of the power in the tap channel and in the main channel. The solid lines are scalar BPM simulation results for the same devices.

We find excellent agreement between the predicted tapping ratio (solid line in Fig. 4) and the measurements for the tap channel, for all nonzero offsets. For zero offset, the light in the tap channel is the result of crosstalk in the demultiplexer. This has been measured in independent demultiplexer devices, and is in the order of -40 dB. The measured tapping ratio is in the range of -25 to -10 dB. However, the lower bound is limited by the mode demultiplexer's crosstalk, and could safely be less than -30 dB. The measured power in the main channel also matches the simulations to within ±0.05 dB, as does the sum of both channels. The "Sum" series is used as an indicator of excess loss. According to the measurements, it remains below 0.1 dB up to an offset of 2 μm.



(a) (b)

Fig. 5. Wavelength and polarization dependence of typical 3% tap. Net transmission and PDL as a function of wavelength for tap device with an offset of 1.1 μm. (a) Main waveguide channel. (b) Tap channel. Reference waveguide's PDL (dashed lines) included for comparison.

The second set of measurements investigated wavelength and polarization dependence for four identical taps with an offset of 1.1 μm, chosen to yield a 3% tapping ratio by design. Measurement results for a typical device are shown in Fig. 5—the other three devices showed very similar results. Four-point Mueller matrix measurements were performed in the wavelength range of 1510–1640 nm for the main channel, tap channel and a reference single-mode waveguide. The insertion loss of the reference waveguide was -0.9 dB, and its wavelength dependency was less than -0.05 dB over the entire spectral range (not shown). Each channel's insertion loss was normalized to the reference waveguide to yield the average net tap transmission over all polarization states for each wavelength, as can be seen in the bottom half of Fig. 5. The maximal absolute value of PDL was also calculated from the Mueller matrix method for each wavelength, as shown in the top half of Fig. 5. The reference waveguide's PDL has also been included (dashed lines) for comparison.

Measurements of the main channel indicate that the tap has barely contaminated the signal compared to the reference waveguide. WDL of the main channel relative to the reference waveguide is 0.01 dB over the whole 130-nm spectral range, while the PDL remains below 0.05 dB, compared to the reference waveguide's 0.04 dB. The tap channel's net transmission starts at -15.75 dB at 1510 nm and monotonically decreases to -16.1 dB at 1640 nm. This can be partly accounted for by simulation results that show a linear decrease of 0.2 dB in the excitation of the high-order mode at the long wavelength end of the spectrum. The tap channel's PDL is around 0.2 dB over the C-band, decreasing to 0.02 dB at 1625 nm and then rising again. Keeping in mind that the PDL shown in Fig. 5 is of absolute value, it is reasonable to assume that the PDL changes sign at this wavelength. Independent measurement results for the adiabatic demultiplexer device [11] show that PDL remains constant at around 0.1 dB over the entire wavelength range, suggesting that in the tap case, the offset contributes to the

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[3] The net transmission shows the actual penalty for introducing the tap to a given optical circuit and should be used when considering cascaded devices. In many cases, it also simplifies the analysis of the device, allowing one to filter-out extrinsic effects, such as fiber coupling losses, from the device's intrinsic proprieties.

PDL via interference between different excited modes in a wavelength dependent manner.

We conclude with a few comments on the device's robustness to process induced deviations from the nominal design. The mode exciter, being a simple lateral waveguide offset, is inherently robust, as can be seen by the excellent agreement between the simulated and measured tapping ratios in Fig. 4, and the consistency of the four identical devices. Simulations for the demultiplexer show that the device's transmission loss is insensitive to variations from the nominal coupler gap in the range of -0.7 to $+0.3$ μm to within ± 0.05 dB. This has also been confirmed experimentally [11]. Simulations also show that variations in the width of the narrow waveguide w_1 or the wide waveguide w_2 in the range ± 0.5 μm do not affect the main channel, while the tap channel suffers excess loss <0.5 dB. This compares favorably with the sensitivity analysis of MMI couplers in [7], especially when considering that here the relative errors in waveguide geometry are much greater. Finally, a similar tap was designed and implemented in a different process with a 2-μm-high core and $\Delta n = 1.5\%$ index contrast, where we also found excellent agreement between the simulated and measured tapping ratios as a function of offset, and similar superior optical performance.

Another aspect of the usability of the device is the sensitivity to temperature changes, since temperature stabilization adds considerable complexity to the packaging of PLC devices. Since our optical tap was originally conceived as a component in a larger optical circuit with other components requiring temperature stabilization [20], we did not perform experiments to specifically analyze the practical operational temperature range for the tap device. On the other hand, we claim that the adiabatic nature of the design should render the device insensitive to temperature changes. Silica's refractive index has a typical temperature dependence of 1.15×10^{-5}/K. From the paraxial equation, we see that for wavelengths of order ~1600 nm this is equivalent to changing the wavelength by -1.8×10^{-2} nm/K, while keeping the actual temperature of the device constant. Since we have demonstrated that the device is wideband over a range of over 100 nm, we can translate this into a very wide practical temperature range. Note, however, that this simplistic analysis doesn't take stress effects into account, which may change the waveguides' birefringence with a much stronger temperature dependence. Still, for birefringence temperature dependence of order 5×10^{-4}/K, a similar calculation shows that we should get an operational temperature range of about 100 K.

V. SUMMARY

The novel design is a tap consisting of two functional stages, a mode exciter which determines the tapping ratio, and a modal demultiplexer for separating the tap signal from the main channel. The device has been successfully implemented in a silica on silicon PLC. Measurements show that the tapping ratio can be accurately predicted by scalar BPM simulations, and that the tap introduces low excess loss, and can be tuned to a tapping ratio of at least -30 to -10 dB. The introduction of the tap to an optical circuit has *negligible effect on the main signal* being tapped, while the tapped signal exhibits low WDL and PDL over a very wide spectral range. Further improvement of these warrants investigation of the offset design. The design is robust and can be easily implemented in different processes.

The design's superior optical performance and robustness are a result of its adiabatic nature. This, however, reflects on the device's major drawback, since the adiabaticity is achieved at the price of a long device, especially when compared to MMI-type couplers. The maximum practical tapping ratio of -10 dB can also deem the device unsuitable for certain applications where other types of couplers are usable. Yet, in applications where critical optical performance was the driving factor, especially when considering that the main signal suffers virtually no degradation, we found that the tap design presented here proved to be the best solution, even at the expense of increased length.

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