# Intensive Study on Compact Integrated Optic Couplers Using Grating Geometry

**Bidyut Deka, Aradhana Dutta, and Partha Pratim Sahu**

**Abstract** In the paper, tooth structured grating-assisted (GA) configuration for 2 × 2 compact directional coupler (DC), two-mode interference (TMI) coupler and multimode interference (MMI) coupler have reported for an intensive study using a sinusoidal mode simple effective index method (SM-SEIM) centric mathematical model. It is found that beat length of GA-TMI coupler is ~22.3 μm which is almost 50% compact in size with comparison to the conventional TMI coupler and is ~25% that for conventional directional coupler. The power imbalance with grating-assisted structures increases as that of fabrication tolerances which are slightly higher compared to conventional TMI coupler.

**Keywords** Integrated optics · Planar waveguide · Grating · Simple effective index method · Directional coupler · Grating coupler

## 1 Introduction

The compact planar waveguide-based optical device and its components have become obligatory for implementation of large-scale integration in photonic integrated device (PID) [1–6] for accomplish of increasing bandwidth requirements in contemporary high speed communication. As the fundamental components of integrated circuit, such as optical couplers (DC/TMI/MMI) and switches with smaller in size have been growing interests due to the compactness and simple fabrication process. The

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grating-assisted geometry has appeared highly promising and is thus introduced in the integrated optical couplers for further compactness that are very much obligatory for large-scale-integration of PID. Polarization sensitiveness along with higher fabrication tolerances gives additional advantage. The previous works [7–9] have discussed the coupling characteristics with a few detail study such as polarization sensitiveness and fabrication tolerances based on finite difference time domain (FDTD) method for the tooth structure grating-assisted TMI coupler.

In this paper, a detail intensive analysis of compact directional coupler (DC), two-mode interference (TMI) coupler and multimode interference (MMI) coupler with tooth structured grating geometry have been carried out using a sinusoidal mode centric simple effective index method (SM-SEIM) [2, 10–13] based mathematical model for accurate analysis of modal coupled power. Dependence of beat length on coupling separation gap between access waveguides with a fixed value of *S* bending loss for tooth structured grating-assisted directional coupler (GA-DC), grating-assisted two-mode interference (GA-TMI) coupler and grating-assisted multimode interference (GA-MMI) coupler are shown. Coupling behavior for DC, TMI and MMI couplers with tooth structured grating geometry have discussed and then compared with conventional structures.

## 2 Grating-Assisted Structure and the Principle

Figure 1 shows three-dimensional (3D) schematic view of 2 × 2 tooth structured grating-assisted directional coupler (GA-DC) having tooth-shaped grating-assisted coupling region with dimensions (length ~ *L*, coupling separation gap ~ *h* between

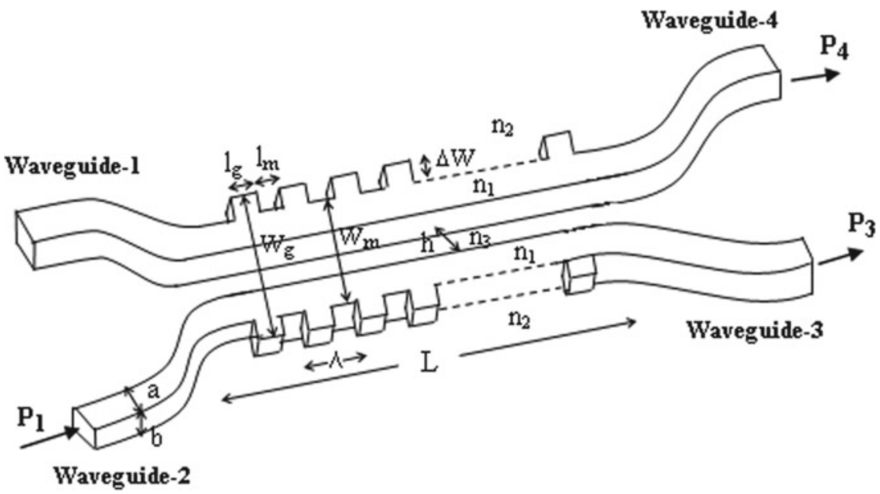



**Fig. 1** Schematic 3D view of 2 × 2 directional coupler with tooth structured grating geometry

the two-channel waveguides), one pair of input single mode access waveguides (Waveguide-1 and Waveguide-2) of core size (width ~ $a$, thickness ~ $b$) and another pair of single mode output access waveguides (Waveguide-3 and Waveguide-4) of similar dimensions, respectively. The coupling region with tooth structured grating geometry is consisting of two-channel waveguides incorporated with tooth structured grating placed close to each other. In the coupling region, the guiding layer of width $W_m$ (~$2a + h$) and grating layer of width $W_g$ (~$W_m + 2\Delta W$) are placed alternatively where $\Delta W$ is the width of grating teeth. In this study, rectangular tooth structured grating is used for higher compactness and simplification of implementation. The grating structured coupling section is consisting of N total number of grating period, $\Lambda = l_m + l_g$; where $l_m$ denotes the guiding layer's length of width ($S = m$) and $l_g$ gives grating layer's length of width ($S = g$), respectively. Refractive index of core layer and cladding layer are $n_1$ and $n_2$ respectively, whereas $n_3$ is refractive index of coupling gap cladding section. For input power ~ $P_1$ launched at input lower most access Waveguide-2, the respective output optical powers obtained through the Waveguide-3 (as bar state) ~ $P_3$ and Waveguide-4 (as cross state) ~ $P_{4.}$

Once the mode field with propagation constant $\beta_i$ ($\lambda$) is launched as input signal through single mode input access Waveguide-2, inside the tooth structured grating-assisted coupling region modes are excited. In coupling section, based on comparative phase difference among the excited modes, light powers are coupled at end of the section through the output single mode access waveguides (Waveguide-3 and Waveguide-4). As fundamental and first-order mode are carrying most of optical power, the beat length which defines the coupling length required for a phase shift ~ $\pi$; of optical coupler with $N$ total number of grating period (~$\Lambda$) is found as,

$$L_\pi = \left[(N+1)\,l_m + Nl_g\right] = \frac{\pi}{\left[\left(\beta_{00}^m - \beta_{01}^m\right) + \left(\beta_{00}^g - \beta_{01}^g\right)\right]} \tag{1}$$

where $\beta_{00}^S$ and $\beta_{01}^S$ denote propagation constant for the fundamental and first-order modes irrespective to guiding layer ($S$ ~ $m$) and grating layer ($S$ ~ $g$), respectively. As ($S$ ~$m$, ~$g$), the width, $W_m = W_g$ and Eq. (1) signifies coupling length for conventional structures.

For high-index contrast waveguide, mode field penetration in lateral outside direction of waveguide is negligibly small where input modal field profile of the $i$th mode, $H_i(x)$ for tooth structured grating-assisted coupling section can be approximated as,

$$H_i(x) = \sin\left[(i+1)\frac{\pi\, x}{W_g}\right] \tag{2}$$

Thus, the optical powers at end of tooth structured grating-assisted coupling region are either coupled toward output access waveguides or diminishes out at end of grating structured channel waveguide. Since all guided modes traveling through the grating structured coupling section will contribute to mode field of output access waveguides, thus, mode fields in $M$th access waveguide can be express as

$$H_M^S(x,L)=\sum_{\substack{i=0\\S=m,g}}^{1}H_{M,i}^S(x,L)=\sum_{\substack{i=0\\S=m,g}}^{1}c_{M,i}\,H_i(x)\exp\left[j\left(\beta_0^S-\beta_i^S\right)L\right] \tag{3}$$

where $L=[(N+1)l_m+Nl_g]$ and $c_{M,i}\approx\sqrt{C_{M,i}^S}$ are contribution coefficient of $i$th mode at $M$th access waveguide, estimated using sinusoidal mode centric simple effective index method (SM-SEIM) [10–12] based numerical model as,

$$\begin{aligned}\frac{C_{M,i}^S}{C_0}=&\frac{\pi^2}{16b^2k^2\left(n_1^2-n_2^2\right)}\\&\exp\left\{-hk\left(n_{\text{eff}}^2-n_2^2\right)^{1/2}\right\}\left[\exp\left\{bk\left(n_1^2-n_2^2\right)^{1/2}\right\}-\exp\left\{-bk\left(n_1^2-n_2^2\right)^{1/2}\right\}\right]\\&+\frac{\pi^2}{16b^2k^2\left(n_1^2-n_3^2\right)}\\&\exp\left\{-hk\left(n_1^2-n_3^2\right)^{1/2}\right\}\left[\exp\left\{bk\left(n_1^2-n_3^2\right)^{1/2}\right\}-\exp\left\{-bk\left(n_1^2-n_3^2\right)^{1/2}\right\}\right]\end{aligned} \tag{4}$$

where for TE mode,

$$C_0=\frac{0.4}{F_C}\times\frac{\left(n_1^2-n_{\text{eff(TE)},S}^2\right)\sqrt{n_{\text{eff(TE)},S}^2-n_2^2}}{n_{\text{eff(TE)},S}\left(n_1^2-n_3^2\right)\left[W_S+\frac{2}{k_0\sqrt{n_{\text{eff(TE)},S}^2-n_2^2}}\right]} \tag{5}$$

$$F_c=\frac{3(1+0.2h)}{\left\{13.5+185\left(\beta_0^S-\beta_i^S\right)\right\}h} \tag{6}$$

$$n_{\text{eff(TE)},S}=\beta_{\text{TE}(i)}^S\left(\frac{\lambda}{2\pi}\right);\quad S=m,g \tag{7}$$

The normalized output coupling power at $M$th access waveguide of tooth structured grating-assisted directional coupler (GA-DC) can be written as,

$$\frac{P_{M,i}(x,L)}{P_{1,i}(x,o)}=\frac{\left|\sum_{\substack{i=0\\S=m,g}}^{1}H_{M,i}^S(x,L)\right|^2}{\left|\sum_{\substack{i=0\\S=m,g}}^{1}H_{1,i}^S(x,0)\right|^2}$$

$$\approx \sum_{\substack{i=0\\S=m,g}}^{1} C_{M,i}^{S} H_i^2(x)$$
$$+ \sum_{\substack{i=0\\S=m,g}}^{1} \sum_{\substack{j=1+i\\S=m,g}}^{1} \Bigg[2\sqrt{C_{M,i}^{S} C_{M,j}^{S}} H_i(x) H_j(x)$$
$$\times \cos\left\{ \sum_{\substack{i=0,j=i+1\\S=m,g}}^{1} \left[(N+q_S)(\beta_i^S - \beta_j^S) l_S\right] \right\}\Bigg] \tag{8}$$

where $P_M^i = \left|H_{M,i}^S(x, L)\right|^2$ and $i, j = 0, 1$ denotes even mode and odd mode such that $j > i$, $q_S = 0, 1$ refers to grating layer ($S$ ~ $m$) and guided layer ($S$ ~ $g$), respectively, total number of grating period ~ $N$ and $C_{M,i}^S$, $C_{M,j}^S$ are the contribution coefficients for $i$th, $j$th modes that signifies the field contribution into output access waveguides which can estimated from Eqs. (4), $\beta_i$, $\beta_j$ = propagation constants for ith and jth mode that are calculated using dispersive equations [2]. The guiding width length ~ $l_m$ and grating width length ~ $l_g$ are determined by using the following relation (9) [8, 9],

$$l_S = \frac{\lambda}{4n_{\text{eff}(j,S)}}; \quad S = m,\ g \tag{9}$$

## 2.1 Result and Discussion

Figure 2 shows schematic layout of three-dimensional (3D) tooth structured 2 × 2 grating-assisted directional coupler (GA-DC) along with the beam propagation results at the bar coupling ($P_3/P_1$) state and cross-coupling ($P_4/P_1$) state with $W_m$ = 3.0 μm, $h$ = 0.5 μm, $\Delta W$ = 0.25 μm, $\Delta n$ = 5%, $a$ = 1.5 μm, $b$ = 1.5 μm, λ ~ 1.55 μm obtained by using optiBPM software. It is also show light wave propagation on half coupling (3-dB) state of GA-DC coupler and cross-coupling point obtained by optiBPM software that is based on finite difference time domain (FDTD) method [6, 12]. From the study found that the cross-coupling point is obtained at coupling length of 45.1 μm which is almost close to that obtained by SEIM based on sinusoidal modes.

The schematic 3D layout of 2 × 2 tooth structured grating-assisted two-mode interference (GA-TMI) coupler is shown in Fig. 3 along with the beam propagation results at bar coupling ($P_3/P_1$) point and cross-coupling ($P_4/P_1$) point found by using optiBPM software for $W_m$ = 3.0 μm, $h$ = 0 μm, $a$ = 1.5 μm, $b$ = 1.5 μm, $\Delta W$ =

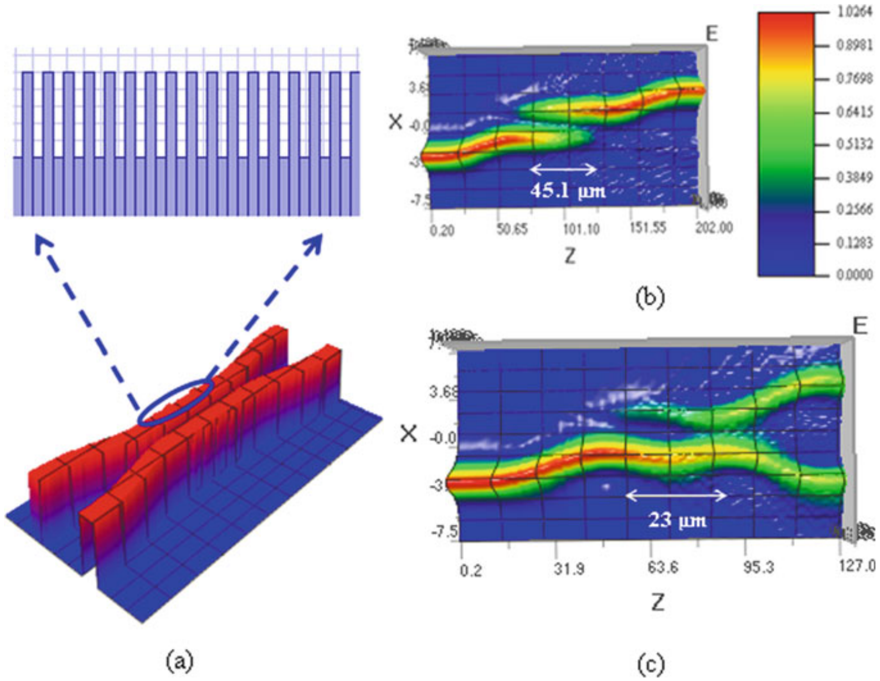



**Fig. 2** Tooth structured 2 × 2 grating-assisted directional coupler (GA-DC) along with (**a**) 3D schematic layout and BPM simulation results for (**b**) cross-state of beat length ~45.1 μm and (**c**) 3-dB coupler of beat length ~23 μm

0.25 μm, $\Delta n = 5\%$, $\lambda \sim 1.55$ μm, respectively. It is found that cross-coupling beat length ~22.3 μm which is equivalent to the result obtained by SM-SEIM.

Figure 4 shows 3D device layout of the tooth structured 2 × 2 grating-assisted multimode interference (GA-MMI) coupler along with beam propagation simulation results estimated using optiBPM software at the bar coupling ($P_3/P_1$) state and cross-coupling ($P_4/P_1$) state with $W_m = 7.0$ μm, $\Delta n = 5\%$, $\Delta W = 0.25$ μm, $h = 4$ μm, $a = 1.5$ μm, $b = 1.5$ μm, $\lambda \sim 1.55$ μm. The coupling length of GA-MMI coupler obtained as ~40.1 μm and 3-dB coupler of beat length ~20.2 μm, respectively. Further, a comparative analysis for beat length ($L_\pi$) versus $\Delta n$ (%) for tooth structured GA-MMI, GA-DC and GA-TMI couplers with teeth height $\Delta W \sim 0.25$ μm and that of conventional couplers (structures with $\Delta W \sim 0$ μm) is shown in the plot Fig. 5. The figure signifies that as Δn increases, the beat length reduces. This is obtained that GA-TMI coupler has the lesser beat length compared to other types of couplers.

In Fig. 6, the relative study of normalized bar and cross-states coupling powers distribution has shown with respect to grating numbers (~$N$) which can be estimated using Eqs. (1)–(9) for tooth structured grating-assisted two-mode interference (GA-TMI) coupler of coupling separation gap, $h \sim 0.0$ μm, directional coupler (GA-DC) for $h \sim 0.5$ μm and multimode interference (GA-MMI) coupler for $h \sim 4.0$ μm with

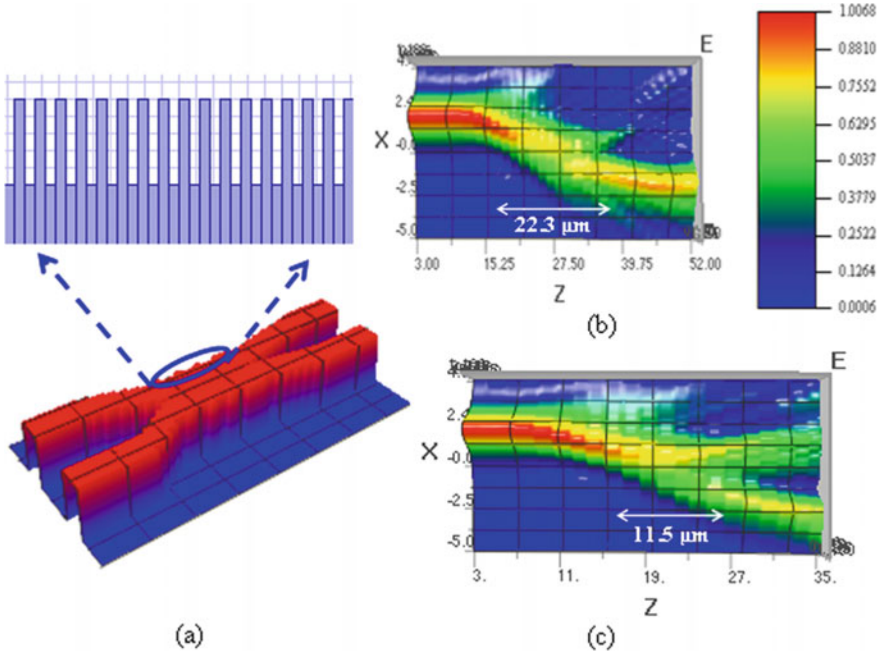



**Fig. 3** Tooth structured 2 × 2 grating-assisted TMI (GA-TMI) coupler along with (**a**) 3D schematic layout and BPM simulation results for (**b**) cross-coupling state of beat length ~22.3 μm and (**c**) 3-dB coupler of beat length ~11.5 μm

$\Delta n = 5\%$, cladding index ~ 1.45, $a = b = 1.5$ μm, $\Delta W$ ~ 0.25 μm, $l_m = l_g =$ 0.27 μm and wavelength (λ) ~ 1.55 μm, respectively. From Fig. 7, it is observed that the peak cross-state coupling power ($P_4/P_1$) is found at beat lengths corresponding to the values of $N$ ~ 41, 70, and 85 with respect to the tooth-shaped GA-TMI, GA-MMI and GA-DC, respectively. Thus, the beat lengths for GA-DC, GA-MMI and GA-TMI couplers calculated using Eqs. (1) are ~45.1 μm, 40.1 μm and 22.3 μm, respectively.

Further, these planar waveguide-based conventional DC, TMI coupler and MMI coupler with waveguide designed parameters are then fabricated and experimentally tested using waveguide materials, SiON as the core layer along with $SiO_2$ cladding layer. From the experimental results as shown in Fig. 7, the beat lengths of conventional TMI coupler ($h = 0$ μm, $\Delta W = 0$ μm) and conventional MMI coupler (with $h = 4$ μm, $\Delta W = 0$ μm) are found as ~45 μm and ~80 μm, respectively, whereas for conventional DC (with $h = 0.5$ μm, $\Delta W = 0$ μm) is ~91 μm with $\Delta n = 5\%$. In the graph, respective cross and 3-dB coupling points are indicated by the dot, and star signs show optiBPM simulation results along with experimental results and SEM photographs of developed DC, TMI coupler and MMI coupler, respectively.

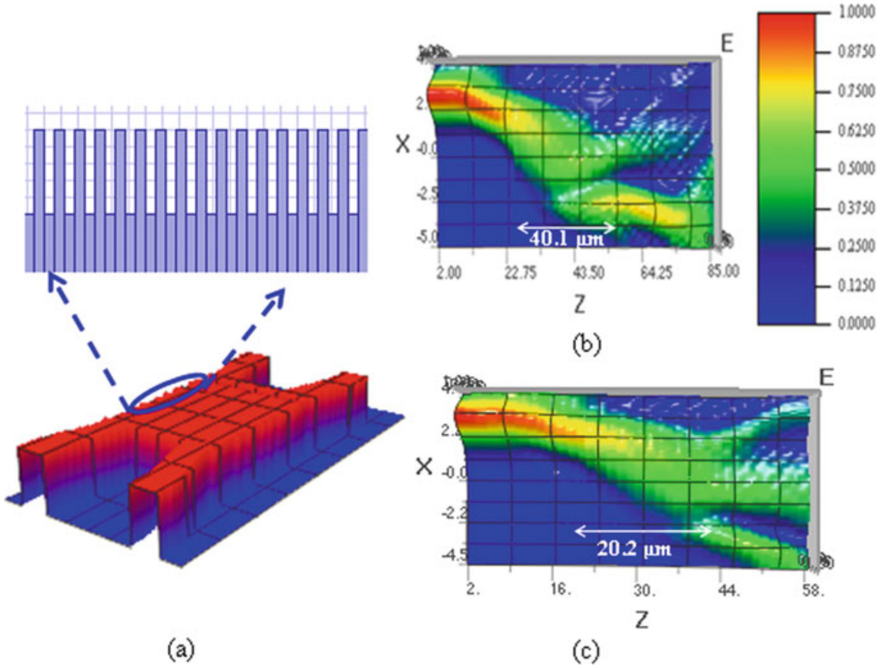
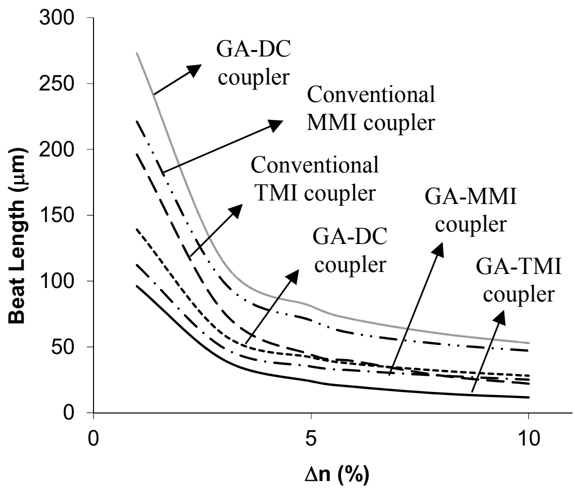



**Fig. 4** Tooth-shaped GA-MMI coupler with (**a**) 3D layout and BPM results for (**b**) cross-coupling state of $L_\pi$ ~ 40.1 μm and (**c**) 3-dB coupler of $L_\pi$ ~ 20.2 μm, respectively

**Fig. 5** Beat length ($L_\pi$) versus index contrast ($\Delta n$) for tooth structured grating geometry with $\Delta W$ ~ 0.25 μm and conventional structures (where $\Delta W$ ~ 0 μm)



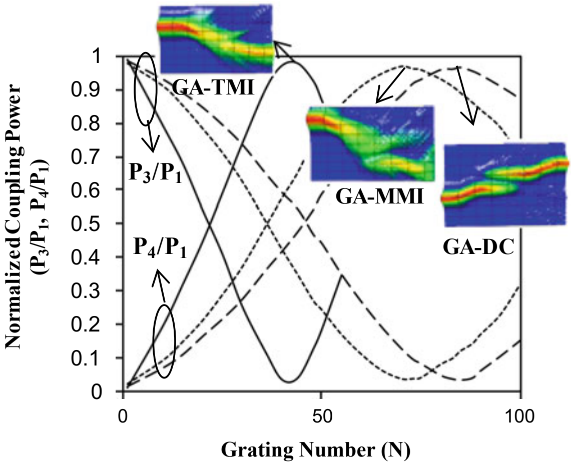



**Fig. 6** Normalized bar and cross-state coupling power distribution versus grating number for tooth structured GA-TMI coupler with coupling gap, $h = 0.0$ μm (solid line), multimode interference (GA-MMI) coupler (dashed lines) for $h = 4.0$ μm and directional coupler (GA-DC) (dotted lines) for $h = 0.5$ μm with cladding index ~1.45, $\Delta n = 5\%$, $a = 1.5$ μm, $b = 1.5$ μm, $\Delta W = 0.25$ μm and λ ~ 1.55 μm, respectively

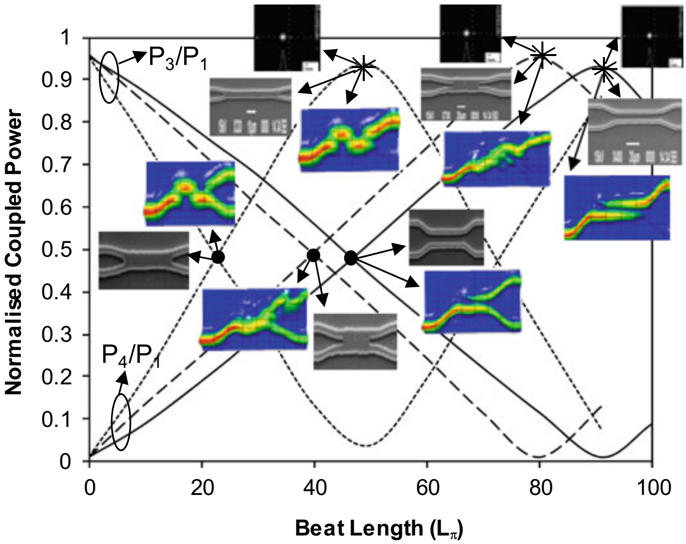



**Fig. 7** Normalized coupling power versus beat length using SM-SEIM-based mathematical model for conventional TMI coupler, MMI couplers and directional coupler, along with BPM simulation results and experimental results, respectively

## 3 Summary

In the paper, a detail comparative study of coupling behavior for tooth structured grating-assisted two-mode interference (GA-TMI) coupler, multimode interference (GA-MMI) coupler and directional coupler (GA-DC) have been presented using a mathematical model based on sinusoidal mode centered simple effective index method (SM-SEIM). The results are compared to the conventional coupler geometry and verified with beam propagation method (BPM) simulation results obtained by using commercially available optiBPM software. It is established that GA-TMI coupler has shorter beat length compared to other couplers.

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