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Efficient evanescent wave coupling conditions
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We studied evanescent wave coupling behavior between low index-contrast upper-level waveguides
and thin-film Si and Ge photodetectors on SOI and germanium-on-insulator (GOI) substrates,
respectively. We present a simple and intuitive leaky-mode phase-matching model using a
ray-optics approach to determine the conditions for efficient coupling, both in 2D and 3D structures.
It is shown that the presence of leaky modes that are phase-matched between the waveguide and the
Si or Ge photodetector layer is the key condition for efficient coupling. Our approach was compared
to other methods, such as finite-difference time domain (FDTD)/beam propagation method (BPM)
and mode analysis. We report that, depending on the way a waveguide photodetector device is
designed, waveguide-to-photodetector coupling efficiency may or may not be critically sensitive to
design parameters, such as the photodetector layer thickness. As an example, the stark contrast
of coupling behavior in the two most popular Ge photodetector structures integrated with Si rib
waveguide versus channel waveguide is shown. The device design factors and the trends that affect
such coupling sensitivity are identified and explained in the paper. © 2011 American Institute of

I. INTRODUCTION

Silicon and germanium photodetectors are important parts of group IV photonic devices, which have attracted
great interest in recent years.1–3 Silicon nanophotonics has the potential to be seamlessly integrated with Si complemen-
tary metal-oxide-semiconductor (CMOS) integrated circuits (IC) and provide an optical alternative solution to the con-
ventional electrical metal interconnects, which are facing limitations due to heat generation and limited bandwidth.

Due to the lower absorption coefficients of group IV semiconductor materials at communication wavelengths
compared to those of compound semiconductors, Si and Ge photodetectors with surface-normal illumination design often
suffer from the trade-off problem between quantum efficiency and bandwidth, as evidenced by many previous experimental reports.4–7

However, integration of a photodetector with a waveguide enables one to overcome the performance limits of
surface-illuminated photodetectors, as it allows designs that decouple the photon-absorption path and the carriers-
collection path from each other. Such benefit of waveguide-integrated design is particularly prominent for group
IV photodetectors and, therefore, is an essential criterion for well-designed waveguide-integrated Si and Ge photon-
detectors. Since 2007, there have been many reports on waveguide-integrated germanium photodetectors,8–18 some of which particularly demonstrated their performance enhancement by integration with waveguide, such as high
bandwidth-efficiency product and high responsivity over wide wavelength range well beyond the direct bandgap of
germanium material.8

Thin-film Si and Ge photodetectors built on SOI or GOI substrates can be a good design platform, especially for
upper-level-waveguide-integrated photodetectors, because their buried oxide layer can confine the photo-absorption
process within the photodetector layer more effectively compared to the silicon photodetector built on regular Si
wafers,19–23 or Ge film grown on Si wafers,9 thus preventing optical leakage loss into the substrate and achieving
enhanced quantum efficiency. The use of thin absorbing films helps reduce the transit time of photo-generated car-
riers for high speed response. One such example structure is depicted in Fig. 1(a).

However, the design process for such SOI/GOI thin-film photodetector devices requires special attention in order to
achieve efficient waveguide-to-photodetector coupling, because the existence of a buried silicon dioxide layer in the
SOI/GOI wafer beneath the active photodetector device layer makes the photodetector layer behave effectively as a wave-
guide. In other words, the photons in the photodetector travel a relatively long distance (i.e., \( t_{Si}/t_{Ge} \)) in the longitudinal
direction along the photodetector before being fully absorbed, and such propagation is possible only with certain propagation
modes inside the photodetector (Fig. 1(b)). This phenomenon occurs because thin-film group IV material can absorb only a
small portion of the incident photons at a single path across the photodetector (e.g., for Ge, \( 1/\alpha_{Ge} \geq 4 \mu m \) at \( \lambda \geq 1540 \) nm
and, for Si, \( 1/\alpha_{Si} \geq 17 \mu m \) at \( \lambda \geq 830 \) nm), and the buried oxide provides the total internal reflection to the unabsorbed
photons, thus confining them in the photodetector.
Consequently, the optical coupling from waveguide to detector can be treated as coupling from waveguide to waveguide, and phase-matching between the two waveguides may become a key criterion for efficient coupling. The coupling and absorption rates are then dependent on the device design parameters. This phenomenon can be a practically important issue, particularly for thin-film group IV photodetector design cases, due to their low absorption coefficient, while many practical design cases of III-V waveguide-integrated photodetectors are less affected by this phase-matching-sensitive coupling, as their thicknesses were often greater than or comparable to their absorption lengths because of their high absorption coefficients.

In contrast, in many traditional evanescent wave coupling structures, where the photodetector is built on a plain Si substrate or where the photodetector layer is thick enough compared to the absorption length, the photodetector is a semi-infinite absorbing medium instead of being a waveguide. Therefore, the waveguide-to-photodetector coupling occurs by the regular evanescent wave coupling process. An example is shown in Fig. 1(c), where the phase is easily matched because the propagation vector in the waveguide \( \beta_{\text{WG}} \) always finds its counterpart propagation vector \( \beta_{\text{PD}} \) in Si, whose lateral component \( k_{x,\text{PD}} \) matches \( \beta_{\text{WG}} \). In these cases, therefore, the waveguide-to-photodetector optical coupling is relatively insensitive to design parameter variations.

In this paper, we investigated the efficient waveguide-to-photodetector coupling conditions in waveguide-integrated thin Si and Ge photodetectors on SOI/GOI substrates because such structures are very promising for top-waveguide-integrated photodetectors that can achieve a high bandwidth-efficiency product. A top-waveguide-coupled structure has the potential to be a better fit for on-chip optical interconnections in a general Si CMOS chip architecture, where active devices are fabricated on the substrate and the passive interconnections are built in the upper interconnect levels. The accurate prediction of the evanescent coupling condition is a critical part in designing such a device, in contrast to most previous studies on the waveguide-integrated Si photodetectors, where the Si photodetector was built mainly on Si wafers, a semi-infinite absorbing medium, and, thus, the waveguide-to-photodetector coupling was relatively insensitive to design parameter variations. We developed a unique model based on a ray-optics approach that calculates and predicts the optimum design conditions in a simpler and more intuitive way than other methods, such as FDTD/BPM or mode analysis. We have found that the waveguide-to-photodetector coupling rate in a SiO\(_2\)-waveguide-integrated SOI/GOI photodetector is very sensitive to the wavelength and the photodetector layer thickness variation. However, we also found such coupling sensitivity can be controlled by changing the waveguide design. For example, we demonstrate in this paper that the thin Ge photodetectors grown on very high index-contrast SOI waveguides, the dominant design platform adopted in most of the recently demonstrated waveguide-integrated Ge photodetectors, may not show significant coupling sensitivity to the Ge film thickness, in spite of the Ge film behaving as a waveguide. This condition-insensitive coupling behavior for specific bottom-SOI-waveguide-integrated Ge photodetector cases may be the reason why the study on evanescent wave coupling conditions has received little attention so far, until we address the topic in this paper with more general device design cases. In this paper, we discuss the trend on how the phase-matching-dependent coupling sensitivity is affected by the device design factors. Such information will be useful, particularly for silicon microphotonic, where a large range of possible materials choices for waveguides (Si\(_2\)O\(_2\)N\(_x\) (\(n = 1.45 \sim 2.0\)), Si\(_3\)N\(_4\) (\(n \sim 2.0\)), Si-rich nitride (\(n > 2.0\)), Si(\(n \sim 3.5\)), etc.) and photodetectors (Si, SiGe, and Ge) exist.

II. MODELING AND ANALYSIS

Our model for determining the optimal coupling conditions is based on the postulate that the waveguide-to-photodetector coupling in a structure like the one in Fig. 2(a) can be treated as the directional coupling between two individual waveguides (i.e., one original waveguide and a lossy, slowly absorbing waveguide that functions as a photodetector as well). Therefore, instead of treating the whole coupling structure altogether, we separated the coupling structure into two individual 3-layer structures, as shown in Fig. 2(a). This separation enables us to use a simple ray optics approach in calculating the modes in each 3-layer structure. In this example, we use a Ge photodetector with an absorption coefficient in the range of 1.6 × 10\(^{-1}\) cm\(^{-1}\) at 1550 nm. A similar treatment can be used for Si photodetectors with similar or lower absorption coefficients (e.g., \(\varepsilon_{\text{Si}} \sim 4 \times 10^{-7}\) cm\(^{-1}\) around 850 nm).

The transverse-electric (TE) propagation mode inside the SiO\(_2\)N\(_2\) waveguide is obtained by the self-consistency condition that a wave after each round trip of internal reflections should be in phase with the original wavefront. That is,

\[
\frac{2\pi}{\lambda_0} n_1 d_1 \sin \theta_1 = -\varphi_{1,A} - \varphi_{1,B} + 2\pi m (m = 0, 1, \cdots),
\]

where \(\theta_1\) is the angle of refraction at the Si/SiO\(_2\) interface, \(\varphi_{1,A}\) and \(\varphi_{1,B}\) are propagation phase factors in the Si and SiO\(_2\) layers, respectively, and \(\lambda_0\) is the free-space wavelength.
produced by total internal reflection, the reflection phase shift at the upper boundary A, is introduced by the complex refractive index of the photodetector material. The notations used in the above equation are indicated in Fig. 2(a). From each intersection point in Fig. 2(c) representing each propagation mode, the propagation constant is obtained by neglecting the effect of the imaginary part of the refractive index and treating the Ge waveguide as a lossless waveguide. For the purpose of obtaining the real part of the propagation constant $\beta$, this is an appropriate treatment when higher-order terms of $\kappa^2$ can be neglected. Therefore, similarly,

$$\frac{2\pi}{\lambda_0} n_2 d_2 \sin \theta_2 = -\varphi_{2,B} - \varphi_{2,C} + 2\pi m \ (m = 0, 1, \ldots).$$

At the interfaces B and C, the reflection phase shifts are, respectively,

$$\varphi_{2,B} = -2 \tan^{-1}\left(\frac{\sqrt{1 - \sin^2 \theta_2} - (n_2/n_1)^2}{\sin \theta_1}\right).$$

$$\varphi_{2,C} = -2 \tan^{-1}\left(\frac{\sqrt{1 - \sin^2 \theta_2} - (n_3/n_2)^2}{\sin \theta_2}\right).$$

In Fig. 2(c), the left-hand side (LHS) and the right-hand side (RHS) of Eq. (5) for the TE case are drawn in terms of $\sin \theta_2$. From each intersection point in Fig. 2(c) representing each propagation mode, $\theta_{2,m}$ can be obtained, and the resulting propagation constants in the Ge layer are

$$\beta_{2,m} = (2\pi/\lambda_0) n_2 \cos \theta_{2,m}. $$

For example, with a SiO$_2$N$_y$ waveguide design with $d_1 = 1.2 \ \mu m$ and $n_1 = 1.58$, the TE-mode propagation constant of $\beta_1 = 6.11 \ \mu m^{-1}$ is obtained, as shown in Fig. 2(b). It should be noted that the mode in the SiO$_2$N$_y$ waveguide, as obtained by the method described above, is not completely confined, but leaky toward the germanium photodetector, because germanium has a higher refractive index ($n_2$) than the effective index of the mode ($n_{\text{eff}}$). Still, the decay of the TE mode is very slow, and the mode can be referred to as a "leaky" or "quasi-confined" mode.
between the modes in the SiON waveguide layer and in the Ge photodetector is the determining condition for the best waveguide-to-photodetector coupling. It is noteworthy that, under these conditions, the corresponding mode in the Ge photodetector layer is also a leaky mode, leaking toward the SiON waveguide, because \( n_3 < n_{\text{eff},2} (m = 3) = n_{\text{eff},1} < n_1 \), i.e., the effective index of the mode is smaller than the refractive index of the SiON waveguide core material.

In contrast, at other conditions (e.g., \( d_2 = 0.673 \, \mu\text{m} \), as also indicated in Fig. 2(c)), the modes in the Ge layer are completely confined as \( n_{\text{eff},2} (\beta_2 / k_0 > n_1 > n_3 \) and their propagation constants, \( \beta_2 \), are far from matching that of the SiON waveguide, \( \beta_1 \).

Two-dimensional (2D) finite-difference time-domain (FDTD) simulations (Fig. 3(a) and Fig. 3(b)) show stark contrast in the evanescent coupling behavior when \( d_2 = 0.577 \, \mu\text{m} \) (phase-matched) versus \( d_2 = 0.673 \, \mu\text{m} \) (phase-unmatched). As predicted, at a Ge thickness of \( d_2 = 0.577 \, \mu\text{m} \), coupling into Ge is very efficient and the overall absorption rate is high (Fig. 3(a)). When an efficient evanescent coupling into Ge occurs, the location of the majority of optical power oscillates between the waveguide and the Ge layer. Accordingly, the local absorption rate varies along the coupling length, reaching local maxima where most photons propagate in the Ge layer and local minima where most photons propagate in the SiON waveguide layer (Fig. 3(c)). In contrast, at a Ge thickness of \( d_2 = 0.673 \, \mu\text{m} \), which is far from a phase-matching condition, the evanescent coupling into the Ge layer is so inefficient that almost no absorption occurs in the Ge layer (Figs. 3(b) and 3(c)).

Figure 3(c) also shows that the similar phase-matching-dependent evanescent coupling behavior applies to thin-film Si photodetectors on SOI substrates as well. For example, at \( d_{2,\text{Si}} = 653 \, \text{nm} \), which satisfies the condition \( \beta_1 = \beta_2 \), as calculated by the above Eqs. (1)–(8), the waveguide-to-photodetector coupling is very efficient, in contrast to the \( d_{2,\text{Si}} = 717 \, \text{nm} \) case.

The above calculation using Fig. 2 with Eqs. (1)–(8) and its verification by simulation tools in Fig. 3 demonstrate that our leaky-mode phase-matching model, which is based on matching the propagation constants of two separately calculated leaky modes in the waveguide and the thin-film photodetector, effectively determines the design conditions for the best waveguide-to-photodetector coupling rate. Its preciseness is confirmed in Fig. 4, as it indicates the photodetector thickness \( d_2 \) that minimizes \( |n_{\text{eff}, \text{SiON}} - n_{\text{eff}, \text{Si}}|^2 \) by the leaky-mode

![FIG. 3. (Color online) (a)-(b) 2D FDTD simulation of photon propagation in such a waveguide-integrated photodetector as shown in Fig. 2(a), showing efficient waveguide-to-photodetector coupling when \( d_2 = 0.577 \, \mu\text{m} \) and the inefficient coupling when \( d_2 = 0.673 \, \mu\text{m} \), respectively. (c) FDTD-calculated power remaining in the coupling structure along the propagating direction at phase-matched (\( \beta_1 = \beta_2 \), as calculated by Eqs. (1)–(8)) and unmatched conditions (greatest discrepancy between \( \beta_1 \) and \( \beta_2 \), according to Eqs. (1)–(8)) for thin Si/Ge photodetectors. For the Ge photodetector, the parameters shown in Fig. 2(a) with \( d_1 = 1.2 \, \mu\text{m} \) were used. For the thin Si photodetector on SOI substrate, the parameters of \( \lambda_0 = 850 \, \text{nm} \), \( n_1 = 1.52 \), \( d_1 = 1 \, \mu\text{m} \), \( n_3 = 3.6 + i 0.0039 \) were used in the calculation.](https://example.com/fig3.png)

![FIG. 4. Comparison of our model vs BPM/FDTD. (a) Our approach: phase mismatch indicator \( |n_{\text{eff}, \text{SiON}} - n_{\text{eff}, \text{Si}}|^2 \) calculated from Eqs. (1)–(8) in terms of varying Ge or Si layer thickness, \( d_2 \). (b) BPM simulation: (1-remaining optical energy after 75 \, \mu\text{m} coupling length/input power) × 100(%) , which is mostly absorption, as Ge or Si thickness varies. Inset shows FDTD results near peak.](https://example.com/fig4.png)
phase-matching model (Fig. 4(a)) matches the $d_2$ that maximizes the absorption rate according to the beam-propagation method (BPM)/FDTD optical simulations (Fig. 4(b)), with less than 2 nm error both for Ge and Si photodetectors. Due to simple calculation procedures and its intuitiveness, the leaky-mode phase-matching model can quickly provide the right design parameters for efficient coupling in a thin-film photodetector integrated with a waveguide. By providing initial input values quickly, it may also help save time in the optimization process using BPM/FDTD simulation tools, which otherwise would take many trials and significant computing time before finding the optimized design, if started with arbitrary parameters.

Our approach is also much simpler compared to the conventional mode analysis method, which was employed in several studies to understand a mode in multi-layer structures with complex refractive indices, such as III-V waveguide-integrated photodetectors. The mode analysis, which involves solving the equation in a complex plane, requires more complicated calculations, and its limitation is that the obtained attenuation rate of the mode does not necessarily correspond to the overall absorption rate in the photodetector. The mode analysis method is more complicated to apply to 3D structures, such as the one in Fig. 1(a), while our leaky-mode phase-matching method can be used very effectively, as will be shown later in this paper.

The leaky-mode phase-matching method intuitively explains the resonance-like dependence of the waveguide (WG) to photodetector coupling efficiency on the variation of $d_2$ and $\lambda_0$, shown in Fig. 4(b) and Fig. 5(a), respectively. Equation (5) contains the parameters $d_2$ and $\lambda_0$ only in the left-hand side of the equation. Therefore, as $d_2$ or $\lambda_0$ varies, the slope of the straight line in Fig. 2(c) changes, while multiple RHS curves of Eq. (5) remain unchanged. As the straight line of Fig. 2(c) rotates, a leaky mode inside the photodetector layer toward the SiON waveguide will appear only when the intersecting point in Fig. 2(c) falls onto a narrow range of $\sin\theta$, where $\sin(\cos^{-1}(n_{1,\text{SiON}}/n_{2,\text{Si}})) < \sin\theta < \sin(\cos^{-1}(n_{3,\text{SiON}}/n_{2,\text{Si}}))$ and the coupling efficiency will peak when the phase-matching $\beta_1 = \beta_2$ is achieved.

As Fig. 2(c) suggests, high absorption peaks will appear periodically with a fixed $\Delta d_2$ and $\Delta(1/\lambda_0)$ interval. From Eq. (5),

$$\frac{2 \pi}{\lambda_0} n_2 (d_{2,m+1} - d_{2,m}) \sin \theta_{2,\beta_1 = \beta_2} = 2 \pi,$$

$$\Delta d_2 = (d_{2,m+1} - d_{2,m}) = \frac{\pi}{(2 d_2 n_2) \sqrt{1 - \cos^2 \theta_{2,\beta_1 = \beta_2}}} \frac{\pi}{\sqrt{k_0^2 n_2^2 - \beta_1^2}} = \frac{1}{k_0 \sqrt{n_2^2 - n_{\text{eff},1}^2}} = 190.4 \text{ nm (GOI)} \text{ or } 129.6 \text{ nm (SOI)}.$$

The above calculated values match well the interval between the peaks in Fig. 4(b). Similarly, for Fig. 5(a),

$$\Delta \left( \frac{1}{\lambda_0} \right) = \left( \frac{1}{\lambda_{m+1}} - \frac{1}{\lambda_m} \right) = \frac{1}{(2 d_2 n_2) \sqrt{1 - \cos^2 \theta_2}} \frac{1}{(2 d_2) \sqrt{n_2^2 - n_{\text{eff},1}^2}} = 0.078 \mu \text{m}^{-1} \text{ (SOI)}.$$

The waveguide-to-photodetector coupling on SOI substrates is very sensitive to the wavelength of photons, $\lambda_0$, as well as the photodetector layer thickness. As Eq. (11) suggests, the absorption peaks in the wavelength scale will have a smaller pitch and smaller full-width-at-half-maximum (FWHM) at a relatively thicker $d_2$. Figure 5(a) shows that a 90-μm-long detector structure with a 1.971 μm Si layer absorbs most light at 850 nm, but absorbs much less at 860 nm, 870 nm, etc. By using this resonance-like absorption behavior, wavelength-selective photodetectors could be made.

In contrast to the great sensitivity of WG-to-PD coupling to the photodetector thickness and photon wavelength shown so far, the deviation of refractive index and thickness of the SiON waveguide from the optimized design decreases coupling efficiency only slightly, as shown in Fig. 5(b) and Fig. 5(c). It can be explained by Fig. 2(b), which demonstrates that the shift of the intersecting point due to the variation of $n_1$ or $d_1$ would not change the propagation constant $\beta_1$ significantly, mainly because the refractive index of SiON is small, relative to that of the photodetector material. Therefore, the change in $|\beta_1 - \beta_2|^2$ is relatively small and the coupling efficiency is only slightly affected. As a result, it would be more critical to calibrate the refractive index of the photodetector material and precisely control the photodetector...
layer thickness during the device fabrication rather than those of the waveguide.

III. MODELING FOR 3D STRUCTURE

A waveguide-integrated photodetector device, such as that shown in Fig. 1(a), requires a 3D modeling method. Unlike the mode analysis method, which would be challenging in 3D structures because of the difficulty of analytical mode calculation, the leaky-mode phase-matching model can still help us obtain conditions for the high coupling efficiency in 3D structures. For an example structure, shown in Fig. 6, we can separate the full SiON WG-coupled Si PD structure into two separate structures of a) a 3D SiON channel waveguide situated on a regular bulk Si substrate and b) a 2D Si slab top-clad by SiON and bottom-clad by a buried oxide layer, as indicated in the Fig. 6(a) inset. The propagation constant of the leaky mode in the Si photodetector, \( \beta_2 \), can be obtained by ignoring the finiteness of the lateral dimension and just following Eqs. (5)–(8). The \( \beta_1 \), the propagation constant of the other leaky mode in the SiON waveguide, can be obtained by using the effective index method (EIM).\(^{33} \)

The 3D SiON waveguide structure on Si is converted to a 2D structure by EIM, and then \( \beta_1 \) can be calculated by Eqs. (1)–(4). In Fig. 6, the optimal coupling conditions obtained by matching the propagation constants \( \beta_1 \) and \( \beta_2 \) (\( d_2 = 0.913 \) \( \mu \)m) show good agreement with 3D BPM simulations in predicting Si layer thickness for the optimal coupling conditions. Alternatively, a finite-difference-method (FDM) mode solver can provide a more accurate calculation of \( \beta_1 \) than the approximate EIM does, and the resulting condition \( d_2 = 0.912 \) \( \mu \)m exactly matches the 3D BPM optimal simulation.

Figure 6(b) shows that the photons will remain mostly inside the SiON waveguide with inefficient coupling to Si. When the phase-matching between leaky modes is satisfied and the coupling to the Si photodetector occurs, photons stay concentrated in the central region without diverging laterally to the wider Si layer (Fig. 6(b)). This is a beneficial phenomenon for the lateral photodetector structure, where the metal contacts are formed at the sides of the WG and the intrinsic region with highest electric field is located beneath the waveguide. The ridge-like coupling structure generates a higher effective index in the central region, contributing to the lateral confinement. When the phase-matching condition is satisfied, the mode keeps oscillating vertically between the top waveguide and the bottom Si layer as they propagate, and in fact, we have observed that varying the width of the Si bottom layer has no significant effect on coupling behavior.

IV. EFFECT OF WAVEGUIDE INDEX-CONTRAST DESIGN AND GEOMETRY ON THE COUPLING BEHAVIOR

The evanescent coupling behavior in the waveguide-integrated photodetector shown so far showed resonance-like coupling behavior, in which the coupling efficiency mostly remains low in a broad range of design parameter variation and incurs sharp efficiency peaks only under specific leaky-modes phase-matching conditions. However, such coupling behavior may be greatly affected by the waveguide design and device geometry, and also vary depending on the polarization of the mode in the waveguide.

Figure 7(a) shows the comparison of the coupling efficiency between GOI photodetectors integrated with two differently designed single-mode waveguides: a low index-contrast \( \Delta \) (\( n_{WG,core} - n_{WG,clad} \)) waveguide (\( n_1 = 1.51, d_1 = 1.75 \) \( \mu \)m) versus a high index-contrast \( \Delta \) waveguide (\( n_1 = 1.8, d_1 = 0.7 \) \( \mu \)m). With the high index-contrast waveguide adopted, the waveguide-to-photodetector coupling rate is enhanced over the overall Ge layer thickness range and a moderately high coupling rate can be achieved, even at out-of-phase conditions. As a result, the resonance-like coupling dependence behavior in a small \( \Delta \) waveguide design case changes into a moderately oscillating, but less selective behavior in the large \( \Delta \) design case. The degree of this change from the resonance-like coupling dependence behavior to the generally enhanced oscillation-like coupling dependence behavior can be estimated by the parameter FWHM/\( H \), as defined in Fig. 7(a) as the full-width at half-maximum (FWHM) of the coupling efficiency peak divided by the peak height (H). Figure 7(b) shows that the parameter FWHM/\( H \) continuously increases, as the waveguide refractive-index scales from the waveguide cases A to D.
refractive index of waveguide core material increases and the waveguide dimensions shrink accordingly). Also shown in Fig. 7(a) is the change in coupling behavior in the transverse-magnetic (TM) coupling case. So far, we have used only the TE polarization cases in all examples shown in the above discussion, because TE polarization shows the phase-matching dependent coupling more clearly and the TE mode operation is employed in many integrated photonic circuits and devices more frequently compared to TM mode, as it is the case, e.g., in the polarization diversity circuits, where the TM mode signal is typically rotated to TE polarization and then goes through TE-optimized photonic functional devices.34–36 With addition of the multiplying factor \( (n_{\text{core}}/n_{\text{cladding}})^2 \) to the above Eqs. (2)–(3) and (6)–(7), just the same method of leaky-mode phase matching can still be used to estimate the efficient coupling conditions, but the most notable change is that, as shown in Fig. 7(a), the TM mode coupling has a much higher coupling rate than the TE mode, in a less selective manner. From the ray optics perspective, the TM incident wave tends to have, along with the existence of the Brewster angle, a significantly lower reflection coefficient and a higher transmission coefficient compared to the TE wave at the boundary between two materials.37 The calculated TM mode in each waveguide tends to have a leaky rather than semi-confined mode with high leakage rate. This is in contrast to a TE mode case, which tends to have its overall mode position shifted away from the interface with the photodetector (as shown in Fig. 3(b) and Ref. 23) and exhibit a significantly lower evanescent coupling rate unless the phase-matching condition is met.

In addition to the \( D_n \) factor, the waveguide geometry and dimensions are another important factor that can directly affect the evanescent coupling behavior. For example, Fig. 7(c) shows that the simple decrease of waveguide thickness \( d_1 \) without the materials variation continuously increases the parameter \( \text{FWHM}/H \) and changes the coupling behavior. We have found that the \( \text{FWHM}/H \) value of the coupling efficiency peak generally increases when the waveguide geometry changes in a way that its size diminishes or the effective index of the mode in the waveguide decreases. Such trends of the \( \text{FWHM}/H \) value change resemble the way that the waveguide materials and design factors affect the evanescent coupling rate in waveguide-integrated PDs formed on regular wafers, which was reported in our previous study.23 Therefore, as the basic tendency for the photons to leave the waveguide and couple to the adjacent photodetector material increases, the underlying evanescent coupling rate in the case of a thin-film photodetector, even at out-of-phase conditions, is enhanced, leading to a higher \( \text{FWHM}/H \) value and a less-selective coupling behavior.

One example of the waveguide design factors making a significant difference in the coupling behavior is the case of thin-film Ge photodetectors integrated with two types of the Si-waveguide-coupled Ge photodetectors. One employs the Si channel waveguide formed on SOI substrate before Ge photodetector is grown, as shown in Refs. 9, 12, 38, and 39. The other has Si rib waveguide structure, as shown in Ref. 10.

![FIG. 7. (a) Dependence of absorption on Ge layer thickness in the coupling structure employing the waveguide design with \( \Delta n = n_2 - n_1 = 0.06 \) (case A, TE and TM mode, respectively) vs the waveguide with \( \Delta n = n_1 - n_3 = 0.35 \) (case D). (b)-(c) Change of the parameter \( \text{FWHM}/H \) of the coupling efficiency peak (b) as the waveguide design changes from low index-contrast to high index-contrast or (c) as only the waveguide layer thickness varies with the given refractive-index of waveguide materials. The different waveguide materials and dimensions cases are listed in the inserted table.](Image)

![FIG. 8. Dependence of absorption on Ge layer thickness in the two types of the Si-waveguide-coupled Ge photodetectors. One employs the Si channel waveguide formed on SOI substrate before Ge photodetector is grown, as shown in Refs. 9, 12, 38, and 39. The other has Si rib waveguide structure, as shown in Ref. 10.](Image)
to a high FWHM/H value. Simulation results, shown in Fig. 8, suggest that the coupling efficiency is very high over the entire Ge layer thickness range. In fact, the experimental reports that employed this structure demonstrated very high coupling efficiency within short coupling lengths, with little attention to any optimal coupling condition.

In contrast, Si rib waveguide-integrated Ge thin-film photodetectors show the phase-matching dependence coupling behavior, as shown in Fig. 8. Due to the waveguide geometry that allows the mode in the waveguide to largely remain in the waveguide core, the effective index is high and close to the index of the core. The trend observed in Fig. 7(c) predicts that FWHM/H would be relatively low for this structure, in spite of the high refractive index of the silicon waveguide core. In fact, the reports on this type of the device showed the relatively lower coupling rate and briefly mentioned that the coupling efficiency depended on the Ge layer thickness without discussing details on the device design. By using the method we provide in this paper, the effective index of a Si rib waveguide, estimated by effective-index-method and Eqs. (1)-(4), or finite-difference-method, turns out to be about 3.565 and the use of Eqs. (5)-(8) predicts the efficient WG-to-PD coupling conditions at Ge thicknesses of 0.72 μm and 1.03 μm. As shown in Fig. 8, such estimation seems to be useful in providing a good starting point for the device design process.

V. CONCLUSION

To design an efficient evanescent coupling structure with group IV, submicron-thick, thin-film photodetectors with absorption coefficients below 5000 cm⁻¹ or so on SOI or GOI substrate may require a very careful determination of design parameters, due to the high sensitivity of the waveguide-to-photodetector optical coupling rate. Using a SiON waveguide and thin Si/Ge photodetectors on a SOI or GOI substrate, we developed a simple and intuitive leaky-mode-phasing-modeling method that explains the evanescent coupling behavior between the waveguide and detector. By uniquely treating the entire structure as a combination of two individual waveguides and analyzing the leaky modes in each separate waveguide using a simple ray-optics approach, we showed that treating this coupling structure as waveguide-to-waveguide coupling is effective, and phase matching between the leaky modes in the waveguide and the photodetector layer is the key condition for efficient coupling. We demonstrated that our method provides a very simple, but also a precise way to find optimal coupling conditions, both for 2D and 3D coupling structures, especially for the designs with TE, low index-contrast, larger-size waveguides. The study showed that the photodetector layer thickness is the most critical factor that needs precise design and process control in this structure. The conditions for peak coupling efficiency re-appear periodically at constant photodetector thickness intervals (in case of low index-contrast SiOₓNᵧ waveguides, about every 130 nm (SOI at λ = 850 nm) or 190 nm (GOI at λ = 1550 nm)), which also can be easily predicted by the formalism and the plots from our approach. Our model can be used to estimate design conditions for efficient waveguide-to-photodetector coupling in a broader range of evanescent wave coupling systems, where the group IV photodetector absorbing material is well-confined and is much thinner than the absorption length (∼1/α) at the wavelength of interest.

We also have discovered that the sensitivity of coupling efficiency to the phase-matching conditions can be greatly affected by the waveguide design factors. The identified trend is that the higher index-contrast Δn (nWG,core − nWG,clad) of the waveguide, as well as the waveguide design with smaller geometry dimensions that lowers the effective index of the mode and the TM mode operation rather than TE mode, tend to enhance the baseline waveguide-to-photodetector coupling rate and thus make the coupling efficiency dependence less selective. This trend was also verified by device examples reported in the recent literature and can be helpful in understanding the evanescent coupling efficiency behaviors in some waveguide-integrated photodetectors in group IV photonics.