Monolithic optical link in silicon-on-insulator CMOS technology

SATA DUTTA,1,* VI SHAL AGARWAL,2 RAYMOND J.E. HUETING,1 JURRIAAN SCHMITZ,1 AND ANNE-JOHAN ANNEMA2

1Semiconductor Components, MESA+ Institute for Nanotechnology, University of Twente, 7500 AE, Enschede, The Netherlands
2Integrated Circuit Design, CTIT, University of Twente, 7500 AE, Enschede, The Netherlands
*s.dutta@utwente.nl

Abstract: This work presents a monolithic laterally-coupled wide-spectrum (350 nm < λ < 1270 nm) optical link in a silicon-on-insulator CMOS technology. The link consists of a silicon (Si) light-emitting diode (LED) as the optical source and a Si photodiode (PD) as the detector; both realized by vertical abrupt n+p junctions, separated by a shallow trench isolation composed of silicon dioxide. Medium trench isolation around the devices along with the buried oxide layer provides galvanic isolation. Optical coupling in both avalanche-mode and forward-mode operation of the LED are analyzed for various designs and bias conditions. From both DC and pulsed transient measurements, it is further shown that heating in the avalanche-mode LED leads to a slow thermal coupling to the PD with time constants in the ms range. An integrated heat sink in the same technology leads to a ∼6 times reduction in the change in PD junction temperature per unit electrical power dissipated in the avalanche-mode LED. The analysis paves way for wide-spectrum optical links integrated in smart power technologies.

© 2017 Optical Society of America

OCIS codes: (040.6040) Silicon; (130.0250) Optoelectronics; (230.3670) Light-emitting diodes; (230.5170) Photodiodes; (130.0130) Integrated optics; (040.1880) Detection; (120.6810) Thermal effects.

References and links
1. Introduction

Monolithically integrated optical interconnects cater to high speed transceiver [1] applications, and to smart-power applications where data needs to be transferred between galvanically isolated voltage domains [2, 3]. The viability of an integrated optical link in silicon (Si) demands a high coupling efficiency (that encompasses the combined efficiencies of the light-emitter, waveguide and the detector) in conjunction with proper galvanic isolation and sufficiently high data rates. Operating a Si light-emitting diode (LED) in forward mode (FM) yields infrared (IR) electroluminescence (EL) ($\lambda \sim 1000$–$1270$ nm) [4–7]. This emission spectrum has a small overlap with the spectral responsivity of Si photodiodes (PDs) [8] resulting in a low internal quantum efficiency (IQE) of the PD. Modulation speeds up to $\sim 1$ MHz have been reported for Si FMLEDs [9].

Operating a Si LED in avalanche mode (AM) yields broad-spectrum EL ($\lambda \sim 350$–$900$ nm) [10–13] with a reported IQE of $\sim 10^{-5}$ [12]. This EL spectrum has a significant overlap with the spectral responsivity of Si PDs [8] resulting in a high IQE of the PD. Optical modulation speeds as high as a few tens of GHz have been reported in Si AMLEDs [14].

Galvanic isolation can be obtained using silicon-on-insulator (SOI) technology. Prior art reported FM optocoupling [15] and AM optocoupling in a $0.8 \mu$m [16], $0.35 \mu$m [17,18], $2 \mu$m [19] and $3 \mu$m [20] bulk CMOS technology with limited galvanic isolation. High isolation voltages ($\sim 3$ kV) have been reported [21], however in an organic optocoupler which is not compatible with standard CMOS technology. Here, a maximum on-off keying speed of only $70$ kHz was reached. SOI technology also offers monolithic waveguiding, which has shown potential applications in high-level hybrid integration for cost-effective high-performance computing [22,23]. Significant advances have been made to integrate optical data communication in the past, but most of them utilized hybrid solutions for inter-chip data transfer [1, 23]. In this work:

1. A fully integrated wide-spectrum ($350$ nm $< \lambda < 1270$ nm) optical link in a commercial $0.14 \mu$m SOI-CMOS technology [24] is demonstrated, which provides $\sim 100$ V galvanic isolation. The link has three components: The light-emitter, the optical channel (waveguide) and the detector. The LED and the PD are implemented as vertical n$^+$p junctions in Si.

2. Optocoupling is shown with the LED biased both in FM and in AM, the two yielding considerably different link properties with respect to link efficiencies in DC operation, parasitic thermal coupling effects and scaling properties.

3. We aim at integrated optical interconnects for smart power applications (e.g. level shifters) which requires highly sensitive photodetectors (e.g. SPADs [25, 26]) given the inherently low light intensity emitted by the LEDs. However, to demonstrate and benchmark our design, we use regular PDs.
This paper is an extension of a recent conference contribution [27] and is outlined as follows. Section 2 presents the design and layout of our optical link. Here the main parameters that contribute to the overall link efficiency are defined. Section 3 describes the DC electrical and EL properties of the LED. Section 4 describes the spectral responsivity of the PD and its I-V characteristics. Sections 5 and 6 demonstrate optical coupling in DC operation of FM and AM operation of the LED. Section 7 addresses the heating in the AMLED, and thermal coupling to the PD. Section 8 presents a comparison between FM and AM operation of our optical link, followed by design recommendations for further improvement of the coupling quantum efficiency. Finally, section 9 concludes our work.

2. Architecture and layout

Figure 1(a) shows the schematic top-view of the optical link consisting of the LED, the dielectric channel (as a waveguide) and the PD. We use the ratio of the LED current $I_{\text{LED}}$ to the short-circuit current ($I_{\text{SC}}$) of the PD [28] (the latter defined as photo-generated current at zero bias voltage) as a measure for the lateral optical coupling. We introduce the coupling quantum efficiency $\eta$ as a figure-of-merit (FOM) of our designs, defined as:

$$\eta = \frac{I_{\text{SC}}}{I_{\text{LED}}} = \eta_{\text{LED}} \cdot \eta_{\text{WG}}(D) \cdot \eta_{\text{PD}},$$

where $\eta_{\text{LED}}$ and $\eta_{\text{PD}}$ represent the IQE of the LED and the PD respectively. $\eta_{\text{WG}}(D)$ is a lumped representation of the overall efficiency of the waveguide (WG) which depends on the mode of LED operation, and on the link length $D$. $\eta_{\text{WG}}(D)$ can be expressed as the product of various components: $\eta_{\text{WG}}(D) = \eta_{\text{in}} \cdot T_{\text{Fresnel}} \cdot \eta_{\text{prop}}(D) \cdot \eta_{\text{out}}$. Here, $\eta_{\text{in}}$ and $\eta_{\text{out}}$ are the efficiencies of extraction of light from the LED to the WG, and that of capture of light from the WG to the PD respectively. $T_{\text{Fresnel}}$ represents the effective transmission efficiency due to Fresnel reflections [29] at the Si-WG interfaces. Values of $\eta_{\text{in}}$, $\eta_{\text{out}}$ and $T_{\text{Fresnel}}$ are constants (independent of $D$) specific to our design and to the mode of LED operation, the detailed calculations of which will not be addressed in this paper. $\eta_{\text{prop}}(D)$ is the $D$-dependent propagation efficiency and takes into account the absorptive losses in the WG and the effective angular aperture of the PD along the direction of propagation. $\eta_{\text{prop}}$ will be further discussed in sections 5 and 6.

Fig. 1. (a) Schematic layout of our optical link. (b) Schematic vertical cross section of the default design of the link along the indicated dashed line in the layout. (c) Die micrograph (top-view) of the default design of our optical link. Figures (a) and (b) are not to scale.
Our optical link involves relatively low values of $\eta$, thereby demanding high electrical power, in particular during AM operation of the LED. This leads to a significant electrical power dissipation, and thereby heating in the AMLED.

Figure 1(b) shows the schematic vertical cross section of the default design of our optical link along the dashed line in Fig. 1(b). Figure 1(c) shows the die-micrograph. The LED and the PD consist of vertical abrupt $n^+ p$ junctions enclosed by medium trench isolation (MTI) for galvanic isolation down to the buried oxide layer. The substrate is lowly p-doped Si. A vertical window is opened in the cathode ($n^+$) contact and silicide layer formation is suppressed in the active areas (except at the contacts) to enable vertical measurement of the EL-spectra through an optical fiber. The LED and PD are separated using STI (composed of SiO$_2$). In addition, a variation of the link has been designed by placing a heat sink to its vicinity. This heat sink is a handle wafer contact [30], which is a vertical polysilicon column extending from the active SOI layer down to the handle wafer. In this design, $D$ is varied from 10 $\mu$m to 60 $\mu$m in steps of 10 $\mu$m.

3. LED: electrical and optical behavior

The optical link is operated with the Si LED either in FM or AM. Figure 2 shows the $I$-$V$ characteristics of the LED on a semi-log scale, measured at an ambient temperature $T_0 = 300$ K. An almost unity ideality factor is obtained for forward bias voltages $< 0.8$ V, while the series resistance becomes prominent for at a higher bias. In reverse bias, the current rises sharply near the avalanche breakdown voltage ($V_{BR}$). Using the definition of breakdown at an arbitrarily chosen current [31] $I=1$ $\mu$A, we find $V_{BR} = 16.8$ V.

![Fig. 2. Measured $I$-$V$ characteristics of the LED at $T_0=300$ K in reverse and forward bias on a semi-log scale. Measurements are done using a Keithley 4200 SCS.](image)

The EL micrographs in AM and FM LED operation are depicted in Figs. 3 (a) and 3(b), respectively. In particular for the AMLED, the emission dominates along the $n^+$ edge closest to the $p^+$ contact due to current crowding and field enhancement. In Fig. 3(b), we see the IR light emission extending well outside the diode’s junction area, in line with the longer absorption length for IR light in Si. Figures 3(c) and 3(d) show the EL-spectra of the AMLED and the FMLED respectively at various current levels at $T_0 = 300$ K. The FMLED emits in the IR ($\sim$1000-1270 nm) [4–7]. The AMLED exhibits broad-spectrum ($\sim$350-900 nm) EL, similar to the ones reported and modeled earlier [13, 32]. Ripples are observed in the AM EL-spectra in the range 600 nm $< \lambda < 800$ nm, which appear due to Fabry-Perot interference in the back-end. The optical intensity increases linearly with increasing $I_{FMLED}$ or $I_{AMLED}$. 
Fig. 3. Magnified die top-view along with the corresponding EL-micrographs for (a) the AMLED captured with a XEVA-257 camera and (b) for the FMLED captured vertically with a XEVA-320 InGaAs camera from Xenics. (c) EL-spectra of the LED at various current levels at \( T_0 = 300 \) K for avalanche mode and (d) forward mode operation, measured vertically by a 50 \( \mu \)m multi-mode optical fiber feeding an ADC-1000-USB spectrometer (for AM-EL) and an AvaSpec-NIR256-1.7 spectrometer (for FM-EL) from Avantes. The arbitrary units in (c) and (d) are independent.

4. PD: electrical and optical behavior

The PD current \( I_{PD} \) is sensitive to both EL-intensity \( L \) (dependent on \( \lambda \)) and the junction temperature \( T_j \) \([28]\). It is the sum of the regular junction current and the photo-generated current (equal to \( I_{SC} \)):

\[
I_{PD} = I_0(T_j) \cdot \left[ \exp \left( \frac{qV_{PD}}{k_BT_j} \right) - 1 \right] - I_{SC}(L, \alpha_{Si}(\lambda, T_j)),
\]

where \( I_{SC}(L, \alpha_{Si}(\lambda, T_j)) = -I_{PD} \) at \( V_{PD} = 0 \), with the negative sign representing current flow from the cathode to the anode. \( I_{SC} \) depends on \( L \) and on the Si absorption coefficient \( \alpha_{Si}(\lambda, T_j) \). Also, \( q \) is the elementary charge and \( k_B \) is the Boltzmann constant, and \( I_0 \) is the dark current of the PD. Upon rearranging Eq. (2), the open-circuit voltage \( V_{OC} \) can be expressed in terms of \( I_{SC} \):

\[
V_{OC}(L, T_j) = \left( \frac{k_BT_j}{q} \right) \cdot \ln \left[ 1 + \frac{I_{SC}(L, \alpha_{Si}(\lambda, T_j))}{I_0(T_j)} \right].
\]

An increase in only \( L \) at a fixed \( T_j \) leads to an increase in both \( I_{SC} \) and \( V_{OC} \). An increase in only \( T_j \) at a fixed \( L \) also results in an increase in the \( I_{SC} \) since \( \alpha_{Si}(\lambda, T_j) \) increases with temperature \([33]\), but \( V_{OC} \) decreases with increasing \( T_j \). In AM operation of the LED, the higher electrical power leads to heating in the AMLED. This in turn leads to a rise \( T_j \) (not observed in FM operation). This is reflected from the \( I-V \) characteristics of the PD for various \( I_{AMLED} \) in our default design (without heat sink) as shown in Fig. 4.
Fig. 4. $I$-$V$ characteristics of the PD under AMLED operation at $T_0=300$ K for various $I_{AMLED}$ for the default design without heat sink. $I_{SC}$ increases with increasing $I_{AMLED}$. $V_{OC}$ first increases and then decreases for higher $I_{AMLED}$, an indication of junction heating. Measurements are done using a Keithley 4200 SCS.

Fig. 5. (a) TCAD simulated PD responsivity at $T_0 = 300$ K as a function of photon wavelength when the junction is illuminated by a monochromatic, unpolarized and unidirectional light source at a fixed optical power $P_{opt}$. (b) Calculated responsivity of the PD weighted by the normalized spectral irradiance of the LED in AM and FM. Note that heating effects are not included in this calculation.

The PD $I_{SC}$ is strongly dependent on the spectral distribution of emission of the LED. Along the same lines of the "matching factor" as introduced in [34], this dependence can be expressed by an emission-specific responsivity $S$ defined as:

$$S = \int E(\lambda) \cdot \frac{I_{SC}(\lambda)}{P_{opt}} d\lambda,$$

(4)
where $E(\lambda)$ is the normalized spectral irradiance of the LED, such that $\int E(\lambda) \, d\lambda = 1$. $I_{SC}(\lambda)$ is the PD $I_{SC}$ when illuminated by a unidirectional monochromatic source having a fixed optical power $P_{opt}$. In Fig. 5(a) the TCAD simulated (in Sentaurus vL-2016.03) spectral responsivity of the PD, defined as $I_{SC}(\lambda)/P_{opt}$, is shown at $T_0 = 300$ K, excluding any heating effect. Default $\lambda$-dependent values of $\alpha_{Si}(=4\pi/k/\lambda)$ at a fixed $T_0 = 300$ K were used. Figure 5(b) plots the integrand in the right hand side of Eq. (4) as a function of $\lambda$ with $E(\lambda)$ being obtained from the measured EL spectra. The value of the emission specific responsivity $S$ in AMLED operation is 100 times higher than in FMLED operation. This is expected due to a higher $\alpha_{Si}(\lambda, T_j)$ of the PD junction [35, 36] for shorter $\lambda$. The overall link efficiency $\eta$ is discussed in the next two sections.

5. Coupling efficiency and waveguide in FM LED operation

In forward mode operation, the IQE of Si FMLEDs is reported to be $\sim 10^{-3}$ [4]. Figure 6 shows the measured coupling quantum efficiency $\eta$ versus $I_{FMLED}$ for different values of $D$ at $T_0 = 300$ K. A gradual increase in $\eta$ is observed with increasing $I_{FMLED}$. This trend indicates that the current is mainly diffusion-dominated [37], Auger recombination in the LED is not significant and the non-radiative recombination process is mainly Shockley-Read-Hall [35], the rate of which decreases with increasing $I_{FMLED}$.

![Fig. 6. Measured $\eta_{FM}$ versus $I_{FMLED}$ for different values of $D$ at $T_0=300$ K.](image)

Figure 7(a) shows the measured $I_{SC}$ of the PD versus $D$ for three values of $I_{FMLED}$. $I_{SC}$ decreases monotonically with increasing $D$. The mean rate of attenuation $\gamma_{FM}$ is low: $\approx 0.072$ dB $\mu m^{-1}$. Pure isotropic transmission cannot explain this $D$-dependence because it would have resulted in a sharper attenuation ($\propto D^{-2}$), which is not observed. The trend can be explained by the formation of two lateral slab waveguides in our design as shown in Fig. 7(b). The back-end waveguide has a high index Si$_3$N$_4$ core sandwiched between a lower and an upper SiO$_2$ cladding layer formed by the STI and the inter-metal dielectric respectively. These dielectrics have a low absorption in the entire spectral range of interest [38, 39]. The high index SOI layer forms an additional waveguide with low absorption losses for photons with $\lambda > 1 \mu m$ [33]. For simplicity, we assume that propagation occurs at near critical angles of incidence ($\theta_c$). Hence, the effective index of the combined waveguide along the propagation direction ($x$-axis) is $n_{core} \cdot \sin \theta_c \approx n_{SiO2}$, where $n_{core}$ represents the refractive index of the nitride or the SOI core layer. Consequently, the
observed $D$-dependence is captured in the propagation efficiency $\eta_{prop}$ and is primarily due to the reduction in the lateral aperture of the PD as derived using geometrical ray optics as follows.

![Graph](image1)

Fig. 7. (a) Measured and modeled $I_{SC}$ of the PD versus $D$ for three values of $I_{FMLED}$. $I_{SC}$ decreases with increasing $D$ as the angular aperture of the PD reduces. (b) Simplified cross-section of the link showing the position of two possible waveguides in FM coupling and the refractive indices for each material. An exemplary ray diagram and a fundamental mode wavefront are shown in each waveguide for a point source of light at the LED junction.

![Diagram](image2)

Fig. 8. (a) Simplified 2-D ray diagram of the top-view of our design, with $W = 45 \mu$m. Photons that are incident below the critical angle $\theta_c$ can emerge into SiO$_2$ prior to being guided through the nitride or the SOI layer. (b) Calculated maximum angular aperture of the PD for increasing $D$.

Figure 8(a) shows a simplified 2-D ray diagram of the top-view of our design for a point source of light. According to Snell’s law, the effective 2-D aperture $\theta_{Si(max)}$ of the PD can be defined as the largest angle of incidence at the Si-SiO$_2$ interface for which the emergent ray is intercepted by the PD active area:
\[ \theta_{\text{Si(max)}}(D, W) = \sin^{-1} \left[ \frac{n_{\text{SiO}_2}}{n_{\text{Si}} \cdot \sqrt{1 + \left( \frac{D}{W} \right)^2}} \right], \]

(5)

where \( n_{\text{SiO}_2} \) and \( n_{\text{Si}} \) are the average refractive indices over the spectral range of \( \text{SiO}_2 \) and \( \text{Si} \) respectively. Note that \( \theta_{\text{Si(max)}} \) has an upper bound of \( \theta_c \approx 21^\circ \), which is the critical angle at the \( \text{Si-SiO}_2 \) interface. As \( D \) increases for a fixed \( W \) (as in our experiment), \( \theta_{\text{Si(max)}} \) decreases (as shown in Fig. 8(b)), leading to a proportional reduction in the optical coupling. In addition, the absorption losses in the core and cladding are also \( D \)-dependent [40]. We can model these combined effects using the following relation:

\[ I_{\text{SC}}(D) = a \cdot \theta_{\text{Si(max)}} \cdot \exp(-b \cdot D), \]

(6)

where \( a \) and \( b \) are fit parameters obtained using the least squares method. A good agreement is obtained between the modeled and measured trends as shown in Fig. 7(a). The fit value of \( a \) is proportional to \( I_{\text{SC}}(D = 10 \, \mu\text{m}) \). The fit value of \( b \approx 10 \, \text{cm}^{-1} \) is in good agreement with the reported [33] \( \alpha_{\text{Si}}(\lambda = 1.1 \, \mu\text{m}) \). This indicates that the SOI waveguide is dominant in FM coupling.

6. Coupling efficiency and waveguide in AM LED operation

![Fig. 9. Measured \( \eta_{\text{AM}} \) versus \( I_{\text{AMLED}} \) for different values of \( D \) at \( T_0 = 300 \, \text{K} \). A heat sink is present in these designs.](image-url)

The avalanche mode EL spectrum of the LED peaks in the visible range as shown in Fig. 3(a). The IQE of Si AMLEDs is reported to be \( \sim 10^{-5} \) [12]. Figure 9 shows the measured \( \eta \) versus \( I_{\text{AMLED}} \) for different values of \( D \). Note that a heat sink is present in these designs. The dependency of \( \eta \) on \( I_{\text{AMLED}} \) reflects the efficiency of radiative recombination in the AMLED, which is sensitive to the current level. We observe a weakly increasing \( \eta \) with increasing \( I_{\text{AMLED}} \), indicating that the injection level is moderate enough not to cause a droop in the radiative efficiency owing to Auger recombination [35]. Further, \( \eta \) is observed to be relatively less sensitive to \( I_{\text{AMLED}} \) as compared to the situation in forward mode. This is because \( I_{\text{AMLED}} \) is dominated by impact ionization, which has a stronger bias dependence [41] as compared to that of forward mode diffusion current.
Comparing Fig. 9 with Fig. 6, we also observe that for a given $D$ and LED current, the coupling quantum efficiency in AM is always higher than in FM. This is mostly due to the combined effect of a lower AMLED IQE and a stronger AMLED-PD spectral overlap as compared to that of the FMLED (see Fig. 5(b)).

Figure 10(a) shows the measured and modeled $I_{SC}$ of the PD versus $D$ for three values of $I_{AMLED}$. $I_{SC}$ decreases monotonically with increasing $D$. Due to the small absorption lengths ($\sim 1 \mu m$) in Si for short wavelengths emitted by the AMLED, the SOI layer does not serve as a WG. Thus, only the back-end WG formed by the high index Si$_3$N$_4$ core and the surrounding SiO$_2$ cladding can serve as the waveguide as shown in Fig. 10(b). The observed attenuation in AM coupling can also be modeled by Eq. (6). Fit parameter $a \propto I_{AMLED}$, and $b \approx 130 \text{ cm}^{-1}$. Note that $\gamma_{AM} > \gamma_{FM}$, because AM coupling occurs only through the back-end dielectric WG. The optical thickness ($n_{\text{core}} \cdot t$) of the nitride core is $\sim 10$ times smaller than that of the SOI waveguide core, and the Si$_3$N$_4$ surface roughness is likely higher than that of the SOI. Both will lead to higher waveguide attenuation.

7. Heating in the AMLED and thermal coupling

DC operation: Heating is significant in AMLED operation and the photodiode junction temperature $T_j$ is affected by the LED power consumption $P_{AMLED}$ according to $\Delta T_j \propto P_{AMLED}$ [42, 43]. Therefore, the rise in $I_{SC}$ is partly contributed by this $T_j$ (see section 4). Heating is more pronounced in SOI technology as compared to bulk Si technology due to the relatively poor thermal conductivity [44, 45] of the buried oxide layer in the former.

Extracting $\Delta T_j$ and separating the independent contributions of EL intensity $L$ and junction temperature $T_j$ to the total $I_{SC}$ are not possible analytically as $V_{OC}$ and $I_{SC}$ are related by an implicit equation (Eq. (3)) with coupled dependencies on $L$ and $T_j$. We, therefore, do it empirically [27] from the measured PD I-V characteristics by obtaining explicit and independent calibration maps: $I_{SC}(L)$, $I_{SC}(T)$, $V_{OC}(L)$, and $V_{OC}(T)$. Here $T$ represents the temperature variable in general without distinguishing between the junction and the ambient. The relations of $V_{OC}$ and $I_{SC}$ of the PD with $L$ and $T$ are calibrated independently by using a commercial off-chip LED (to isolate optical from thermal effects) and by varying $T_0$ at a fixed $L$. The off-chip LED
emits at 650 nm with a FWHM of 40 nm, which approximately emulates the emission spectrum of the AMLED.

![Figure 11](image-url)

Fig. 11. De-embedding procedure for separating the contributions of $L$ and $\Delta T_j$ to the total $I_{SC}$ in AMLED operation in the default design (without heat sink): (a) $I_{SC}$ versus $I_{AMLED}$ at $T_0 = 300$ K. (b) Measured $V_{OC}$ (black) for AMLED operation and the calibrated value (green) using the off-chip LED at $T_0 = 300$ K and modeled by Eq. (3). (c) Calibrated $V_{OC}$-$T$ curve and (d) $I_{SC}$-$T$ curve of the PD for various off-chip LED currents (and hence $L$).

The following steps are followed (as shown in Fig. 11) for extracting thermal coupling in DC operation in our default design (without heat sink).

**Step 1:** $I_{SC}$ for a given $I_{AMLED}$ is measured and is assumed to be the sum of $I_{SC}^{(OP)}$ and $\Delta I_{SC}^{(SH)}$, which represent the independent contributions of $L$ (optical) and $T_j$ respectively.

**Step 2:** Figure 11(b) shows the variation of $I_{SC}$ versus $V_{OC}$ of the PD during AMLED operation and the calibrated pure optical variation at $T_0 = 300$ K obtained using the off-chip LED. The deviation of $V_{OC}$ from the calibrated value, at the given $I_{SC}$ obtained in step 1, is recorded.

**Step 3:** Figure 11(c) shows the calibrated $V_{OC}(T)$ for the PD for four different values of $L$ of the off-chip LED. The slope of a linear fit of the $(V_{OC}, T)$ data points yield a mean temperature coefficient $T_{C_{VOC}}$ of -2.5 mV K$^{-1}$. The deviation $\Delta V_{OC}$ obtained in step 2, is then mapped onto the calibrated curve to obtain: $\Delta T_j = \frac{\Delta V_{OC}}{T_{C_{VOC}}}$. 
Step 4: Figure 11(d) shows the calibrated $I_{SC}(T)$ for the PD, with a mean temperature coefficient $T_{C_{ISC}}$ of 0.12 pA K$^{-1}$. The $\Delta T_j$ obtained in step 3 is then used to obtain $\Delta I_{SC}^{(SH)} = \Delta T_j \cdot T_{C_{ISC}}$.

Fig. 12. (a) Rise in PD junction temperature (symbols) owing to heating in the AMLED in the default design of our optical link, following the procedure of Fig. 11. $\Delta T_j$ increases linearly with the LED electrical power $P_{AMLED}$. (b) The separated contributions of increasing $L$ (blue) and increasing $T_j$ (green) to the total measured $I_{SC}$ (red).

Fig. 13. Measured transient waveforms of the pulsed AMLED current $I_{AMLED}(t)$ (top) and the resulting $V_{PD}(t)$ (bottom) when the PD is forward biased with a constant current of $I_{PD} = 1$ mA (a) without heat sink and (b) with heat sink. $V_{PD}$ shows a thermal RC relaxation behavior with a time constant $\tau_{TH}$ of 126 ms without heat sink and 40 ms with heat sink. Note that in this particular measurement, the LED is always operated in AM, which is the source of heat, and the PD is forward biased to suppress the optical dependence of $V_{PD}(t)$. 
Figure 12(a) shows the extracted $\Delta T_j$ values at different $P_{\text{AMLED}}$. Figure 12(b) shows the separated components of $I_{\text{SC}}$. In the default design, around 13% of the total $I_{\text{SC}}$ is contributed by thermal coupling. The slope of $I_{\text{SC}}^{(\text{OP})} - I_{\text{AMLED}}$ curve shows a gradual reduction for high values of $I_{\text{AMLED}}$. This is likely due to the combined $T$-dependencies of the IQE of AMLED and that of $\eta_{\text{WG}}$.

**Transient operation:** The (de-embedded) thermal coupling affects the bandwidth of the link, which in turn, affects the digital bit rates in data transfer. The bandwidth can be characterized by a thermal time constant $\tau_{\text{TH}} = R_{\text{TH}} \cdot C_{\text{TH}}$, where $R_{\text{TH}}$ and $C_{\text{TH}}$ are the effective thermal resistance and capacitance \cite{42,43} of the AMLED-link-PD system.

In order to extract $\tau_{\text{TH}}$, the AMLED is pulsed between "on" ($V_{\text{AMLED}}=25$ V) and "off" ($V_{\text{AMLED}}=15$ V) states at a pulse repetition frequency (PRF) of 1 Hz with a 50% duty cycle and a 5 ns rise time, as shown in Fig. 13(a). In this measurement, the PD is biased at a constant forward bias current $I_{\text{PD}} = 1$ mA. This bias ensures that $V_{\text{PD}}$ is sensitive only to $T_j$ with a measured temperature coefficient $\partial V_{\text{PD}}/\partial T_j$ of $-1.2$ mV K$^{-1}$, and that $\partial V_{\text{PD}}/\partial L$ at a constant $T_j$ and constant $I_{\text{PD}}$ is negligible.

During the "on" phase, the AMLED heats up leading to the heating of the PD, which reduces $V_{\text{PD}}(t)$. In the "off" (cooling) phase, $V_{\text{PD}}(t)$ relaxes back to its ambient value, exhibiting in both phases a first-order thermal RC behavior with $\tau_{\text{TH}} = 126$ ms. Note that the electrical time constant of our set-up ($\sim 5$ ns) contributed by the PD and wiring parasitics is negligible compared to $\tau_{\text{TH}}$ and hence does not affect our measurement.

**Fig. 14.** Measured $\Delta T_j$ of the PD per unit $P_{\text{AMLED}}$ versus increasing $D$ showing a monotonic decreasing behavior. A heat sink is present in the links used in this measurement.

**Effect of heat sink:** $\Delta T_j$ can be reduced by including heat sinks. The heat sink we realized, significantly reduces the effective $R_{\text{TH}}$ of the link and thereby leads to a 6 times reduction in $\Delta T_j$ in DC operation ($\sim 30$ K W$^{-1}$) compared to the same link without the heat sink ($\sim 180$ K W$^{-1}$). The reduction of $R_{\text{TH}}$ also reduces $\tau_{\text{TH}}$ to 40 ms as shown in Fig. 13(b).

**Effect of link length:** The link length $D$ directly impacts the thermal propagation. Using pulsed measurements in all these designs at a PRF of 1 Hz, similar to the one in Fig. 13(b), a monotonic decrease in $\Delta T_j$ per unit $P_{\text{AMLED}}$ with increasing $D$ has been obtained as shown in Fig. 14. Thus longer links have less thermal crosstalk, in agreement with a thermal lumped $\pi$-network model.
with effective lateral \((D\text{-dependent})\) and vertical components of \(R_{\text{TH}}\).

8. Discussion and design recommendations

![Fig. 15. Measured coupling quantum efficiency \(\eta\) in AM and FM coupling versus link length \(D\) for our designs. A linear extrapolation of the data yields a cross-over point \(D = D_T \approx 76 \, \mu\text{m}\).](image)

The main findings reported in sections 5 to 7, and their implications are as follows:

1. Within our measured range of \(I_{\text{LED}}, \eta_{\text{AM}} > \eta_{\text{FM}}\). This result is an interplay of competing phenomena, encompassing \(\eta_{\text{LED}}, \eta_{\text{WG}}\) and \(\eta_{\text{PD}}\). Nonetheless, we show that both FM and AM coupling in standard CMOS is feasible.

2. The coupling efficiency \(\eta\) decreases monotonically with increasing \(D\). The rates of attenuation \(\gamma_{\text{FM}}\) and \(\gamma_{\text{AM}}\) are observed to be almost independent of the LED current. Further, \(\gamma_{\text{FM}} < \gamma_{\text{AM}}\).

3. The different rates of attenuation in FM and AM coupling leads, for our design, to a cross-over point in coupling efficiency around \(D = D_T \approx 76 \, \mu\text{m}\), where the extrapolated measured values intersect as shown in Fig. 15. This indicates that for \(D < D_T\), avalanche mode operation yields a higher \(\eta\), while for longer link lengths forward mode operation of the LED is preferred from a coupling efficiency point-of-view.

4. Measured PD \(I_{\text{SC}}\) is in the order of 10 pA in DC operation at \(T_0 = 300 \, \text{K}\). For our optical link, this would enable data communication with an output (PD) referred signal-to-noise ratio (SNR) of \(\sim 15 \, \text{dB}\) for a bandwidth \(B\) of, for e.g., 1 MHz, where \(\text{SNR} = 10 \cdot \log \left( \frac{I_{\text{SC}}}{2qI_{\text{SC}}B} \right)\). Here shot noise is the main contributor for noise power. Owing to such a low SNR, SPAD based receivers are needed to achieve high-speed data transfer through our link.

5. Heating in the AM operation of the LED leads to an increase in the PD junction temperature \(T_j\). During on-off keying of the AMLED, this leads to a parameter shift in the PD. However, given the significantly long thermal time constants (in the range 40-120 ms), no thermal...
data communication is expected during high speed opto-coupling; thermal coupling will at most lead to DC offsets at the receiver end.

6. AM coupling consumes $\sim 10$ times higher electrical power (in the LED) than FM coupling. However, the reported Si AMLED switching speed ($\sim$ GHz) is $\sim 10^3$ times higher than that reported for Si FMLEDs ($\sim$ MHz). Combined, this indicates that, for digital data communication, a $\sim 100$ times reduction in "energy per bit" can be achieved in AM coupling as compared to FM coupling in Si.

From the analysis in this paper we can formulate several design recommendations to improve the optical link, and in particular its coupling quantum efficiency.

**Coupling in forward mode:** To enhance $\eta_{LED}$, the spacing between the contact and n$^+$ diffusion edge can be increased, which reduces the diffusion current [37]. $T_{Fresnel}$ can be increased by having only one MTI (instead of two) for galvanic isolation between the LED and the PD. $\eta_{PD}$ can be enhanced by having both $d_{PD}$ and $W$ to be $> a_{Si}^{-1}(\lambda)$, where $a_{Si}^{-1}(\lambda)$ is the absorption length in Si. $\eta_{prop}$ can be increased by removing the STI and the nitride layer. The resulting single SOI WG will have a greater optical thickness ($n_{Si} \cdot t_{SOI}$) and lower absorptive losses.

**Coupling in avalanche mode:** $\eta_{LED}$ can be enhanced by increasing the perimeter to area ratio. The LED dimension in the direction of optical propagation can be reduced to the order of $a_{Si}^{-1}(\lambda)$. In addition, reducing the magnitude of $V_{BR}$ of the AMLED can not only increase its power efficiency [13] but also reduces the parasitic thermal coupling. $\eta_{PD}$ can be enhanced by having a lower doping level, which increases the depletion width and hence the responsivity.

For links with SPAD based detectors, this recommendation is beneficial from the viewpoint of having a low dark count rate and high photon detection probability [25]. For the waveguide, $\eta_{in}$ (or $\eta_{out}$) can be enhanced by increasing the contact area between the EL-region of the LED (or the PD active area) and the nitride core. Lastly, $\eta_{prop}$ can be enhanced by patterning the WG on the x-y plane, which would reduce the effect of $D$-dependent angular aperture of the PD.

Improving the coupling quantum efficiency $\eta$ is beneficial for increasing the achievable bandwidth of the optical link, when used for intra-chip data communication. It should be noted that although avalanche-mode LEDs in Si have been shown to exhibit GHz range small-signal modulation speeds [14], the maximum data rate is limited by the SNR at the output of the optical receiver. A 3 Gb/s optical receiver with off-chip illumination ($\lambda = 850$ nm) was reported [46] using PDs in standard 180 nm CMOS, where the input optical power determines the SNR and thereby the bit error rate. On the other hand, if optical intensities are low (like in our monolithic link), high-speed communication is feasible by using highly sensitive SPAD based receivers, which are sensitive to the number of photons received per bit, and thereby relies on $\eta$. Prior art reported SPADs [25, 26] in the same SOI technology. Here, the maximum data rate is limited by the dead-time of the SPAD (depends in turn on bit error rate specifications). For example, a dead-time of $\sim 100$ ns was demonstrated in the work of [26] that translates into a maximum data rate in the order of $\sim 10$ Mb/s. Measuring the maximum achievable data rate in our optical link requires high-speed measurements with RF de-embedding test structures, which we do not have at this time, and is thus still open to future research.

9. Conclusions

1. A monolithic, galvanically isolated, laterally-coupled and wide-spectrum ($350$ nm $< \lambda < 1270$ nm) optical link in 0.14 $\mu$m silicon-on-insulator CMOS technology has been demonstrated. Optical coupling has been analyzed in both forward and avalanche mode LED operation, quantified by the short-circuit current in the photodiode.
2. The link exhibits a higher coupling quantum efficiency in avalanche mode LED operation as compared to forward mode LED operation. Coupling, especially through shorter wavelengths in avalanche mode, is made feasible via silicon dioxide and other inter-metal dielectrics like silicon nitride that form low-attenuation waveguide for the photons.

3. High power dissipation and heating in the avalanche mode LED leads to an increase in the junction temperature of the photodiode, observed to be 180 K W$^{-1}$ (without heat sink) in DC operation of the LED. This is reduced to 30 K W$^{-1}$ by integrating a heat sink. Measured thermal time constants of our design are 120 ms (without a heat sink) and 40 ms (with a heat sink).

4. Further, the coupling quantum efficiency has been experimentally shown to be monotonically decreasing with increasing link length, in agreement with a model that combines geometrical optics and attenuation.

The presented optical link is a potential solution for integrated wide-spectrum optical interconnects for smart power applications (e.g. level shifters) and intra-chip data communication in standard CMOS, when integrated with highly sensitive detectors (e.g. single photon avalanche-diodes) that compensate for the low photon-emission fluxes.

**Funding**

Dutch Technology Foundation (STW) (HTSM 2012, Project 12835).

**Acknowledgments**

The authors would like to thank NXP Semiconductors B.V. for fabricating the devices, S.M. Smits and J.P. Korterik (MESA+ Institute for Nanotechnology, University of Twente) for the experimental support and P.G. Steeneken and M. Swanenberg from NXP Semiconductors for their valuable discussions and chip finishing. The authors also are thankful to the reviewers for their constructive comments which have benefitted this paper.