

High-Speed Data Transmission with Beam-Steering using Silicon Optical Phased Array

Hyun-Woo Rhee, Minchul Kim, Jong-Bum You, Hyo-Hoon Park

School of Electrical Engineering, Korea Advanced Institute of Science and Technology (KAIST),

Yuseong, Daejeon 34141, Korea

dlgusdn2@kaist.ac.kr, fomalhaut15@kaist.ac.kr, youjongbum@kaist.ac.kr, parkhh@kaist.ac.kr

Abstract— Optical wireless data transmission is an emerging complementary technology compared to the radio frequency transmission in specific fields. Silicon based solid-state optical phased array (OPA) has a large advantage on the entire system size, low power consumption and high speed operation. The designed radiator of OPA has 16 channels of grating array with each grating having $20\mu\text{m}$ length and etch depth of 70nm . Grating array radiator has $2\mu\text{m}$ pitch achieving $\pm 22.7^\circ$ beam steering angle. Radiator's output beam has a beam divergence angle of 4° and 6° for each longitudinal and vertical direction. With the designed OPA, we have demonstrated a 5Gbps data transmission in a free-space range of 30cm . Eye diagram was achieved at center and full steered beam position by phase shifting. The extinction ratio of the transmitted eye-diagram was about 7dB verifying that OPA is a promising technology for high-speed wireless data transmission.

Keywords— Optical Phased Array (OPA), Beam Steering, Wireless data transmission, Optical wireless communication, Silicon photonics

I. INTRODUCTION

The optical wireless communication system has gained interest over the years as a complementary technology for radio frequency (RF) communication. Currently RF communication system is mainly used, but cannot access over few Gbps. However, the characteristics of optical radiation makes optical wireless transmission to have high-speed data transmission, unlimited bandwidth, high security and immune to signal interference [1].

Indoor optical wireless transmission can use both visible and infrared bands. Light-emitting diodes (LEDs) are one of the visible light sources that is used for optical wireless data transmission. But, LEDs has a limited modulation bandwidth causing complexity for high speed transmission [2]. Infrared light sources has large bandwidths bringing high speed transmission easily. Considering the laser safety, 1550nm band has the maximum power up to $7\sim 10\text{dBm}$ [3]. Since the main factors of optical wireless transmission are beam power, light noise and free space loss, 1550nm band has the most suitability.

Using the 1550nm band light as the source of optical wireless transmission, one of the main technology being used is microelectromechanical systems (MEMS) [4]. However, MEMS has an undeniable weakness in low steering range, low steering speed, power consumptions and stability.

OPA can be integrated on silicon using CMOS process with small size and high performance [5]. By using the phase shifters, OPA can steer beam in high speed with low power consumption and large steering range. The main issue for OPA to be used in optical wireless transmission is the emitting beam power and the divergence angle. In this paper, we propose a wireless transmission scheme using a designed OPA and demonstrate high speed data transmission.

II. ARCHITECTURE AND DESIGN

We have designed a wireless data transmission scheme using OPA. The scheme is consisted of transmitter and receiver part. Input beam is modulated by an electrical signal and coupled into the OPA chip. Directional output beam of OPA is diverged in free space, reaching the receiver. Diverged beam is inserted to PD by converging lens system. In this process, beam divergence is the key element for the scheme to have high performance. From the designed scheme, we were able to specify the target beam divergence. After fixing the target, we designed the grating radiator to achieve the target beam divergence.

A. Wireless Transmission Scheme

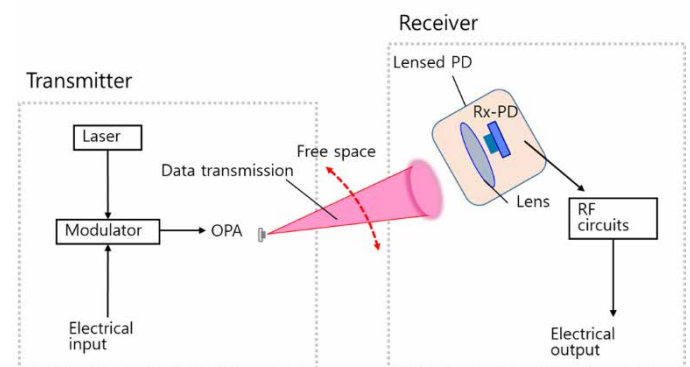


Figure 1. Principle of optical wireless data transmission using OPA

The scheme shows a free space data transmission with beam steering OPA as shown in Fig. 1. The performance of communication is mainly shown as bit-error-rate (BER) and can be derived by equation (1). I_{Rx} and $i_{Rx-noise}^2$ represents the current and the noise current of the receiver.

$$\text{BER} \leq \frac{1}{2} \operatorname{erfc}\left(\sqrt{\frac{I_{Rx}^2}{2I_{Rx-noise}^2}}\right) \quad (1)$$

Current of the receiver (I_{Rx}) and noise current ($i_{Rx-noise}^2$) are obtained from equations (2) and (3), where M is the amplification factor of PD, R_{Rx} is the response of PD, A_{Rx} is the receiving area of receiver, T_{Rx} is the efficiency of lens system, B_{Rx} is the bandwidth of PD, F is the noise factor. Distance of free-space transmission is L and the divergence angle of the OPA's output beam is θ_{div} .

$$I_{Rx} = MR_{Rx}P_{OPA} \frac{A_{Rx}}{\pi \left(L \tan \frac{\theta_{div}}{2}\right)^2} T_{Rx} \quad (2)$$

$$i_{Rx-noise}^2 \approx 2qB_{Rx}(M^{1.7}I_{Rx} + I_{dark}) + \frac{4k_B T B_{Rx} F}{R_{load}} \quad (3)$$

PD's active area has a diameter about $80\mu\text{m}$, T_{Rx} can be presumed as 30% and other coefficients are determined by the product PD. Since we used the commercialized high speed PD, model 818-BB-35 produced by Newport Corporation. Then BER is only determined by free space beam travel range and the emitted power of OPA. High performed wireless transmission has BER less than 10^{-12} . Fig. 2 is derived by equations (1) ~ (3), showing the required beam divergence angle for achieving 10^{-12} BER at 1.5m and 5m range.

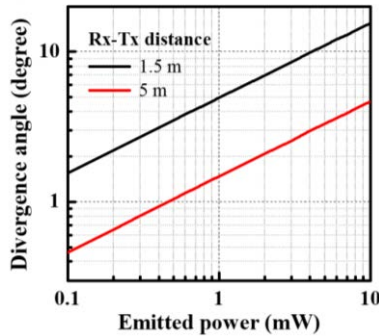


Figure 2. Divergence angle needed to achieve 10^{-12} BER with different emitting power at 1.5m and 5m.

The scheme is mainly focused on indoor data transmission leading the range of beam travel to be estimated as 1.5m. Also, the emitted beam power of OPA is about 1mW due to the chip loss. At a 1.5m beam travel range and 1mW emitting power, the divergence angle of beam should be targeted as 5° .

B. Grating Array Radiator

Divergence angle of OPA's emitting beam is determined by the radiator's structure which is shown in Fig. 3. To achieve small beam divergence in ψ and θ , grating length and array width should be extended respectively [6]. The parameters of the radiator are listed at Table 1. Factors determining the beam divergence, grating etch depth and array number are set as variable.

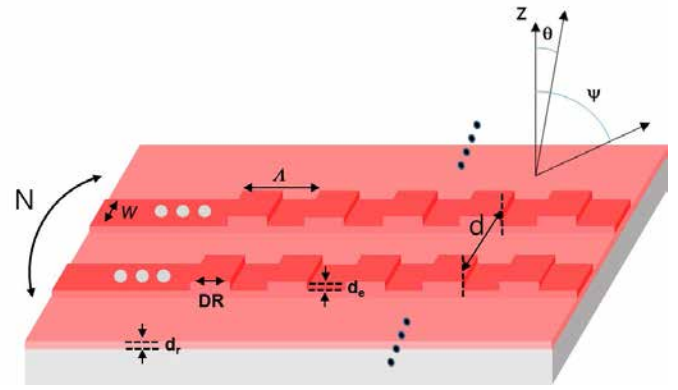


Figure 3. Structure of a grating array radiator.

TABLE 1. PARAMETERS OF RADIATOR

Parameter	Value
Grating period (Λ)	620nm
Duty ratio (DR)	0.5
Top silicon thickness	220nm
Grating etch depth (d_e)	variable
Rib thickness (d_r)	50nm
Grating width	$1\mu\text{m}$
Pixel pitch (d)	$2\mu\text{m}$
Array number (N)	variable

Longitudinal (ψ) beam divergence angle is decided by the grating length. Grating length is mainly depended on the grating etch depth. Deeper the etch depth, more beam leaks at a same length bringing the actual grating length shorter. We have simulated the etch depth's relationship with grating length in FDTD by a single grating radiator. Fig. 4 is the result of the simulation showing that at each etch depth, the divergence angle saturates at some grating radiator length. Beam divergence angle at etch depth for 70nm, 50nm, 30nm saturates to 5.1° , 3.0° , 2.3° respectively. Since the target beam divergence angle was 5° , we have designed our OPA's radiator to have 70nm etched, $20\mu\text{m}$ long grating.

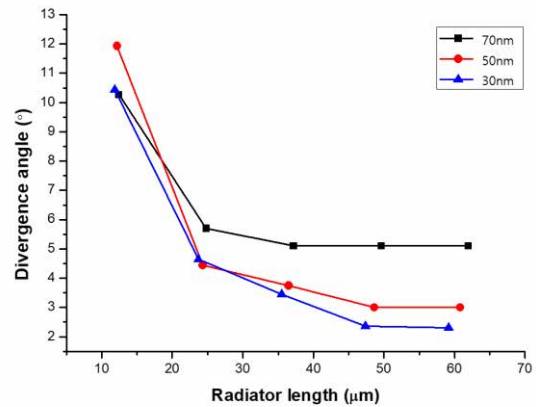


Figure 4. Divergence angle for different radiator length with etch depth of 70nm, 50nm and 30nm.

Vertical (θ) beam divergence angle is decided by the vertical length of the radiator decided by the pixel pitch and number of array. Since the pixel pitch has been fixed as $2\mu\text{m}$, array number decides the θ beam divergence. Equation (4) is the theoretical beam divergence in θ .

$$\theta = \frac{4\lambda_0}{\pi L_g} (\text{rad}) \quad (3)$$

FDTD simulation of grating radiator with different array number is shown in Fig. 5(a). The divergence angle of FDTD simulation is compared with the theoretical value in Fig. 5(b). Simulation results has a larger value than the theoretical value due to the interaction between gratings. Larger the array number, beam divergence gets smaller but the chip scale and the complexity increases. 16 grating arrays can achieve 3.5° , satisfying the target angle.

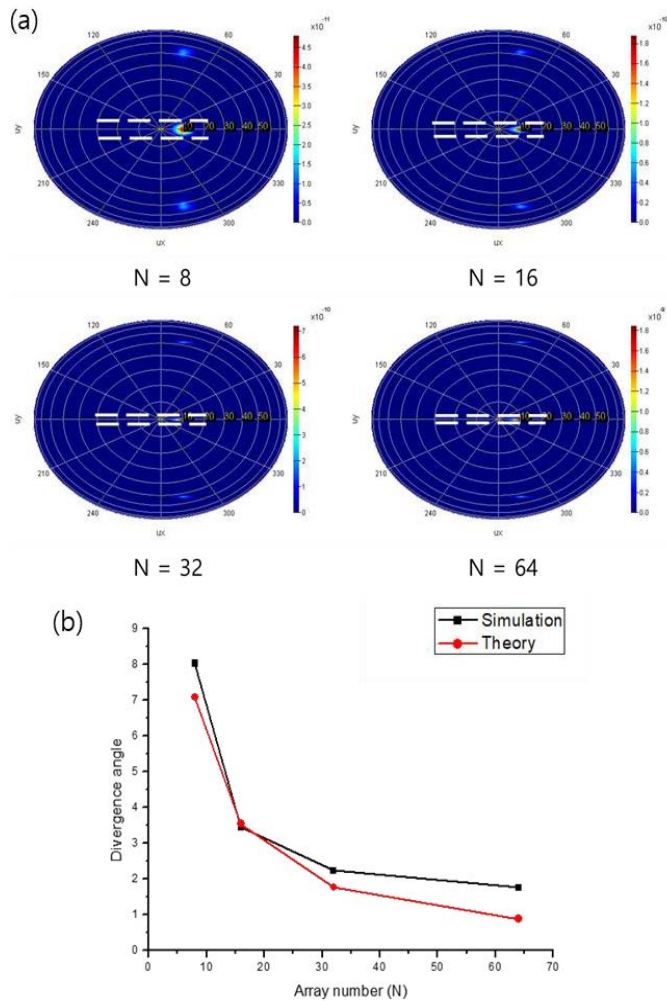


Figure 5. (a) FDTD simulation results for different array number and (b) difference between theory and simulation.

The radiator has been designed as 16 grating arrays, each grating having a $20\mu\text{m}$ length with 70nm etching. It was only to satisfy the standard level for indoor 1.5m data transmission.

III. EXPERIMENTAL SETUP

The proposed indoor high speed data transmission using silicon OPA has been demonstrated experimentally as shown in Fig. 6. OPA has been packaged to PCB board and phased tuned by electrical signal. For fiber coupling, the packaged OPA was placed perpendicular to the ground. We used a high reflective optical mirror coated with silver for redirecting the emitted beam, diverging parallel to the ground. PDs were placed at the center of beam position and 22.5° out of center for fully steered beam position.



Figure 6. Experimental setup used to demonstrate high speed data transmission using packaged OPA.

IV. RESULTS AND DISCUSSION

A. Beam Divergence

OPA's beam divergence was measured before the high speed data transmission was processed. Phase tuned beam was visualized by CCD camera from Xenics after passing a objective lens with NA of 0.6. The divergence angle of the beam had 4° and 6° for longitudinal and vertical direction. The designed radiator had a 3.5° and 5.1° divergence angle in simulation. Difference was inevitable since the phase tuning of all channels wasn't flawless and the fabrication error. The steering angle of the beam was measured up to 45° .

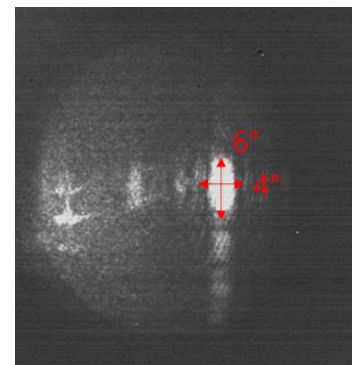


Figure 7. OPA's emitting beam with 4° and 6° divergence angle pictured by CCD camera.

B. Data Transmission

High speed data transmission in free space using OPA was demonstrated as Fig. 6. To show the actual beam steering, PDs were placed at the center and fully steered beam position. Optical modulated signal was continuously emitted from the OPA while beam steering.

Fig. 8(a) and (b) shows the 5GHz eye diagram of the received signal at center and fully steered positioned PD with a free space range of 30cm. When signal is sent to the center position PD, the other PD receives no optical power. The emitting beam of OPA has a high directivity and low noise signal since the extinction ration of two different directional signal has 7.12dB and 6.04dB.

Due to the limitation of PD's active area and concentration lens system, we haven't yet gained results of data transmission over 1m free space range. PD with a higher speed operation up to 28GHz with an open window has an active area of $9\mu\text{m}$ diameter. By solving the converging lens system and up scaling the OPA's radiator, free space data transmission can be available over 20GHz with longer range.

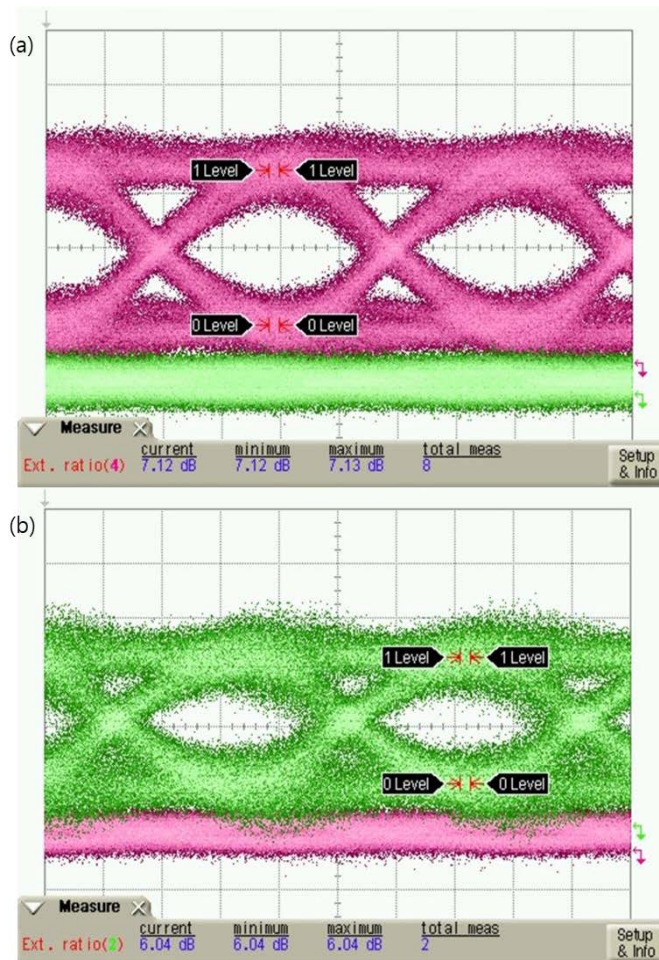


Figure 8. 5GHz eye diagram of PD's received signal at (a) center position, (b) fully steered position.

V. CONCLUSIONS

In conclusion, we have proposed a high speed data transmission using silicon based OPA complementing the free space transmission in current systems. OPA has strong points in scale and power consumptions compared to other optical wireless communication systems. This paper has strongly verified the possibility of OPA in wireless communication by demonstrating a 5GHz data transmission at a free space range of 30cm. The demonstration also shows a low noise and high directional beam steering. Improvements in beam power, divergence angle and the receiver's beam converging system will actualize the ultra-fast data transmission in long ranges.

REFERENCES

- [1] Elgala H., Mesleh R., Haas H.: 'Indoor optical wireless communication: potential and state-of-the-art', IEEE Commun. Mag., 2011, 49, (9), pp. 56–62, doi: 10.1109/MCOM.2011.6011734
- [2] D. Tsonev, S. Videv, and H. Haas, Opt. Express 23, 1627 (2015).
- [3] "Safety of laser products. Part 1: equipment classification and requirements," AS/NZS IEC 60825.1:2014, Standards Australia (2014).
- [4] Arnon S., Barry J., Karagiannidis G., ET AL.(EDs), 'Advanced optical wireless communication systems' (Cambridge University, Press 2012).
- [5] K. Wang, A. Nirmalathas, C. Lim, E.Wong, K. Alameh, H. Li, and E. Skafidas, Opt. Lett. 43, 3132 (2018).
- [6] D. N. Hutchison, J. Sun, J. K. Doyle, R. Kumar, J. Heck, W. Kim, C. T. Phare, A. Feshali, and H. Rong, Optica 3, 887 (2016).



Hyun Woo Rhee received B.S. and M.S. degree in School of Electrical Engineering from KAIST (Korea Advanced Institute of Science and Technology), Korea, in 2017 and 2018. He is now a Ph.D. course in department of Electrical Engineering from KAIST. His current research interests include silicon photonics and optical wireless communication.



Minchul Kim received B.S. degree in School of Electrical Engineering from KAIST (Korea Advanced Institute of Science and Technology), Korea, in 2017. He is now in Master's degree course in School of Electrical Engineering at KAIST. His current research interests include silicon photonics and nano-photonics.



Jong Bum You received M.S. degree in Advanced Device Technology from University of Science and Technology in 2010. He is now a post doctor course in department of Electrical Engineering from KAIST (Korea Advanced Institute of Science and Technology). His current research interests include silicon photonics and nano-photonics.



Hyo Hoon Park received M.S. and Ph.D. degree in department of Materials Science and Engineering from KAIST, Korea, in 1982 and 1985, respectively. From 1985 to 1986, he was a post-doctoral scholar from Stanford University. He was working for ETRI (Electronics Telecommunications Research Institute) since 1997. Since 1998, he is a professor of Electrical Engineering, KAIST (Korea Advanced Institute of Science and Technology). His current research interests include silicon nanophotonics for microprocessor-memory interfaces, 3D chip interconnection, phased-array antenna etc.