Demonstration of Wide-angle Beam Steering Optics in Wavelength-division-multiplexing Indoor Optical Wireless LAN with Dedicated CMOS Imager

Keiichiro Kagawa
Osaka University
2-1 Yamadaoka,
Suita City, Osaka 565-0871, JAPAN
+81-6-6879-7869
kagawa@ist.osaka-u.ac.jp

Jun Tanida
Osaka University
2-1 Yamadaoka,
Suita City, Osaka 565-0871, JAPAN
+81-6-6879-7851
tanida@ist.osaka-u.ac.jp

ABSTRACT

We are developing a new indoor optical wireless LAN system, in which dedicated CMOS imagers are utilized to offer location-aware visually-intuitive wireless communications, wavelength- or space-division-multiplexing high-speed data transfer, and compact hardware. This paper focuses on a wide-angle beam steering optics, which is a key component to realize a compact and wide-angle optical transmitter accessible to the network from anywhere in a room with 5 m by 5 m size. A prototype beam steering lens designed for a near-infrared wavelength of an 850-nm band was fabricated and demonstrated. Experimental results show that the maximum output beam angle was about ±60 degrees, which covers the 5m-by-5m room (when the vertical distance between a hub and a node was 2.0 m), and the optical power efficiency was higher than 0.8 which equals to about 1dB loss.

Keywords

Indoor optical wireless LAN, free-space optical communications, wavelength multiplexing, beam steering, CMOS imager.

1. INTRODUCTION

Free-space optical communications (FSOC)[1] are a key technology to create new generation ultra-fast wireless communication systems. The most outstanding feature of light in free space compared with radio-frequency (RF) electromagnetic waves in respect of wireless communications is two-dimensional *imaging* with lenses, much higher frequency (> 100 THz), and spatial and wavelength parallelism. We believe that the *imaging ability* can dramatically improve the conventional indoor optical wireless LANs [2-4]. Better security and higher data rate than RF wireless LANs are known as benefits of the optical wireless LANs. However, we believe that integration of *imaging* will bring new attractive features to the indoor wireless networks.

We are developing a new indoor optical wireless LAN system that offers a visually-intuitive user interface as well as high-speed data transfer [5]. The key device is a newly-developed dedicated complementary metal-oxide-semiconductor (CMOS) imager [6] with a concurrent optical data acquisition function as a multi-point photoreceiver. The dedicated CMOS imager can not only capture the scene of a room where a wireless network connection is available as an image but also receive multiple fast optical signals concurrently at different pixels of the imager. The *image* can be understood in two ways. One is that it shows the positions of communication nodes or a hub on the scene in a visually intuitive manner. For example, the scene image overlapped with the identifiers (like icons) of the communication nodes or the hub will add a feature of location awareness to the network, which makes the computer network more understandable and user-friendly. The other understanding of *the image* is spatial parallelism. Each light source out of the same line of sight is spatially separated on the image, which implies high-speed optical data acquisition by space-division-multiplexing (SDM) optical communications if the fast optical signals onto different pixels

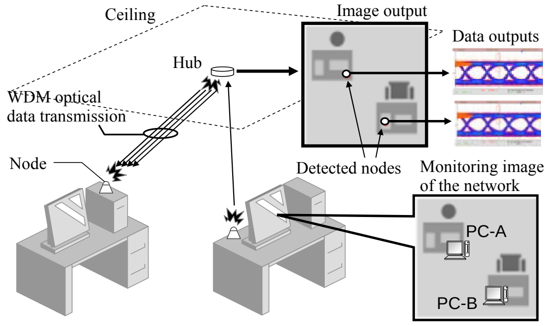

Figure 1. Wavelength-division-multiplexing indoor optical wireless LAN with dedicated CMOS imagers.

Table 1. Specifications of demonstration system.

Covered area	5 m × 5 m (for a ceiling 2 m above nodes)
Wavelength	850 nm band
Maximum channels of multiplexing	4
Data rate	> 1.0 Gbps/ch

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can be read out at the same time. In FSOC, a chromatic dispersive element such as a grating can convert SDM to wavelength-division-multiplexing (WDM) by decomposing a single WDM light beam to multiple spots on the imager. Our dedicated CMOS imager enables a fusion of imaging and FSOC, and realizes multi-gigabit-per-second user-friendly indoor wireless networks. Location awareness also offers a foundation of several ambient services. People in the room can be traced from the captured images at the hub. Personal computers can serve user-dependent services by relating the locations of the personal computers to the people logged on them.

In this paper, we detail a wide-angle beam steering optics, which is a key component to transmit optical signals toward the communication targets in a communication area. In Sec. 2, the compositions of the whole system and the communication modules are described. In Sec. 3, a composition and a design of the wide-angle beam steering optics is mentioned. In Sec. 4, the fabricated prototype of the beam steering lens is experimentally characterized. Section 5 shows the summary and future issues.

2. WDM INDOOR OPTICAL WIRELESS LAN WITH DEDICATED CMOS IMAGER

2.1 System Configuration

Figure 1 and Table 1 show the concept of our indoor optical wireless LAN [7] and the specifications of a demonstration system, respectively. Downlink up to 4.0 Gbps and 1.0-Gbps downlink are projected. The nodes connected to personal computers communicate each other via the hub installed on the ceiling. The significant features of the LAN are that dedicated CMOS imagers are utilized at both of the hub and the nodes as a multi-point photoreceiver as well as a simple imager for detecting the positions of communication target(s) on the scene, and the narrow light beams convey the communication data. To achieve a gigabit data rate, usage of the narrow beam is inevitable to increase the received power at the receiver. The dedicated imager is equipped with two kinds of electric outputs: a temporal series of scene images (movie) and multiple channels of fast optical signals. The fast optical signals can be read out from the limited number of the pixels receiving them at the same time. This feature is called multi-point concurrent data acquisition (MPCDA).

The data link is asymmetric to fully utilize the MPCDA feature of the imager. Uplink is multi-to-one data transfer from multiple nodes to the single hub. The SDM access is suitable for implementing this kind of data transfer, and MPCDA is used for SDM at the hub. On the other hand, downlink is one-to-one access between the hub and a node. To increase the bandwidth of the downlink, the MPCDA is assigned to implement the WDM data transfer.

A simplified sequence to establish a network connection is as follows: 1) capture a movie of the scene by the dedicated imager, and specify the pixels detecting the communication target(s) (hub for nodes and nodes for hub) by image recognition of unique blinking of the position markers attached to the communication module or wavelength filtering in the optical domain, 2) directly read out multiple channels of the fast optical signals only from the identified pixels by use of the MPCDA. After the connection is established, the scene image captured at the hub is transferred to the node, and it is displayed with the identifiers of the nodes (like icons) overlapped. The users can recognize what and where the other communication nodes are.

2.2 Communication Modules

As shown in Fig. 2, the main hardware components of the hub module are laser sources with slightly different wavelengths, a wavelength multiplexer, a beam deflector, and a beam steering lens for the transmitter part, a imaging lens and a dedicated CMOS imager for the receiver part, and a position marker. The position marker is a diffusive light source such as a light emitting diode (LED) to illuminate the whole room, which is used as a position identifier in the first step of the connection establishment. The composition of the node module is somewhat different. It has only a single laser source and no multiplexer in the transmitter

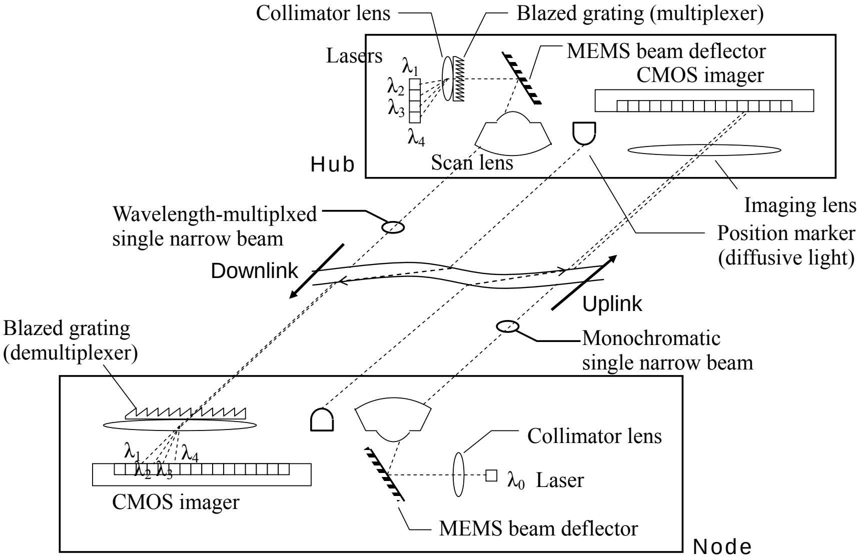


Figure 2. Composition of communication modules.

part, and the demultiplexer is added to the receiver part.

In Fig. 2, deflection of the light beam is introduced by the micro-electro-mechanical-systems (MEMS) mirror [8,9]. However, the amount of the deflection is not enough to cover the whole room. To overcome the limitation, we have proposed a scan lens for amplifying the beam deflection [10].

2.3 Dedicated CMOS Imager

The CMOS imager dedicated to our indoor optical wireless LAN [5, 11] is a fusion of an ordinary CMOS imager and an array of photoreceivers circuits used in optical fibre communications [12,13]. Figure 3(a) and Table 2 show the block diagram and the specifications of the dedicated imager under development, respectively. To implement the MPCDA feature on an imager pixel, each pixel has digital control logics to define the operation mode: imager or photoreceiver mode (Fig. 3(b)). For the signal readout, the pixel has two kinds of output signal lines: one analog image output line and two differential analog photocurrent output lines in both sides of the pixel. The differences between two operation modes are detection schemes of the optical signal. In the imager mode, photocurrent is accumulated at the photodiode so that extremely high photosensitivity is achieved but responsibility is very slow (up to around hundreds of kHz). In the photoreceiver mode, the photocurrent is directly amplified by the transimpedance amplifier (TIA) at the column circuit without accumulation. Therefore, it can detect a high-frequency signal but has low sensitivity. These complementary features are suited to detect the dim marker light in the imager mode and the strong narrow beam for communication in the photoreceiver mode. Refer to Ref. [11] for the details.

3. WIDE-ANGLE BEAM STEERING OPTICS

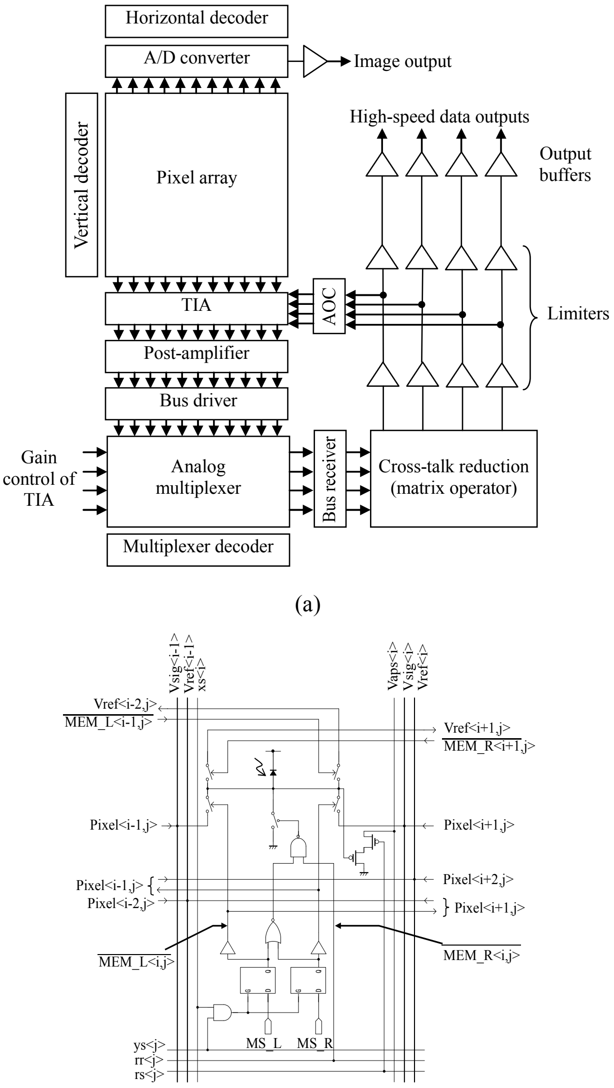
3.1 Configuration

The mission of the optical transmitter is to deliver the narrow laser beam for communication to everywhere in the whole room with a size of more than 5 m by 5 m. For the purpose, we have proposed an optical setup of the beam steering optics shown in Fig. 4. The optical system is composed of three parts: the wavelength multiplexer, the beam deflector, and the magnifier of the beam deflection angle. The feature is that the beam deflection magnifier is inserted in the exit of the beam steering optics to realize a compact and wide-angle optical transmitter.

To combine the laser beams with the wavelengths of λ_1-λ_4 into a single beam, the following equation should be satisfied. Note that δ, $\Delta\lambda$, d, and f_1 are the pitch and the wavelength difference of the adjacent lasers, the pitch of the blazed grating, and the focal length of lens, L1.

$$\delta = \left(\Delta\lambda \big/ d\right) f_1. \tag{1}$$

Because availability of the MEMS mirror satisfying the requirements for the optical transmitter is not good, the beam deflection part is implemented by a combination of a focusing lens (L2) on the two-dimensional miniature stage and a collimator lens (L3). The focusing lens, L2, moves in the plane perpendicular to the optical axis. In this setup, an intermediate image is generated at the relayed image position in Fig. 4. When



(a)

(b)

Figure 3. (a) Block diagram of dedicated CMOS imager and (b) simplified pixel schematic. TIA: transimpedance amplifier, AOC: automatic offset canceller.

Table 2. Specifications of dedicated CMOS imager

Technology	0.18 μm CMOS (5-metal, 1-poly, MiM capacitor)
Chip size	7.5 mm × 10 mm
Operation voltage	2.0 V
Pixel count	180 × 84 pixels
Pixel size	31.25 μm × 62.50 μm
Data channels	4
Data rate	1.0 Gbps/ch (simulation)
Data output standard	LVDS

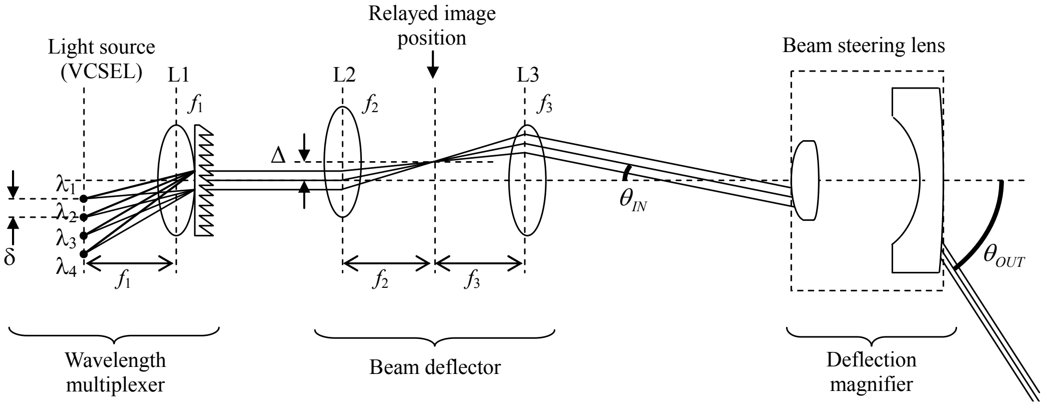


Figure 4. Configuration of light beam transmitter.

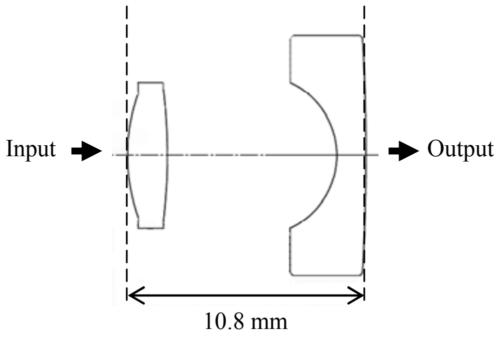


Figure 5. Configuration of scan lens.

the displacement of L2 in one axis is represented by Δ, the output angle of the beam from L3, θ_{IN}, is written by

$$\theta_{IN} = \mathrm{Tan}^{-1}\left(\Delta/f_3\right), \qquad (2)$$

where f_3 means the focal length of L3. The beam steering lens as the beam deflection magnifier amplifies the input angle of the collimated beam, θ_{IN}, with a certain angle gain to obtain the large output angle, θ_{OUT}. With the beam steering lens, a wide range of beam deflection angles can be achieved for a small displacement of L2.

3.2 Beam Steering Lens

The beam steering lens has a reverse-telephoto-type configuration [14]. We have designed and fabricated a prototype lens whose structure and specifications are shown in Fig. 5 and Table 3, respectively [15,16]. The lens is designed for wavelengths of a 850-nm band, and its maximum field of view is 140 degrees. The maximum gain of the beam angle is 3.5. Because the left surface of the rear lens has a large curvature, the rear lens is composed of aspherical surfaces to minimize the output beam distortion. The feature of this beam steering lens is large tolerance of the alignment along the optical axis due to its infinite conjugate design, which makes the assembly easier.

4. EXPERIMENTS

The prototype system of the beam steering optics with the fabricated beam steering lens was demonstrated and characterized experimentally. For simplicity, a single laser source on the movable stage (mechOnics, Model MS15, travel of 3.5 mm, maximum speed of 1.5 mm/s) was placed directly at the relayed image position in Fig. 4. WDM was not implemented in this prototype. A laterally-single-mode GaAs vertical-cavity surface-emitting laser (VCSEL) was used as a laser source (FujiXerox, Model VCSEL-AS-0001, wavelength of 840-860 nm, maximum beam divergence of 20 degrees (FWHM), optical output power of 2 mW). f_3 was set to 2.2 mm. For this configuration, the minimum and the maximum of Δ should be about ±0.8 mm. Figure 6 shows the experimental setup.

Table 3. Specifications of wide-angle scan lens.

Wavelength	845-851 nm
Focal length	2.1 mm
Field of view	140 degree (max)
Overall length after assembly	10.2 mm
Working distance	5.0 mm
Acceptable input beam diameter	1.0 mm
Effective output diameter	10 mm
Beam angle gain	3.5 (max)
Material	K-SFLD6 (front), PBK40 (rear)

Figure 7(a) shows the measured relationship between the input and the output beam angles of the beam steering lens. The maximum output beam angle was about 66 degrees in the experiments, which was large enough to cover a 5 m-by-5 m room when the vertical distance between the hub and a node was larger than 2 m. The maximum angle gain was 3.4, which showed good agreement with the design. The beam size on the receiver plane is a significant concern because it defines received power, namely, the signal integrity. The beam size strongly depends on the radiation angle and the size of the laser source. Figure 7(b) shows the beam sizes measured on the ceiling 173 cm above the beam steering optics. The radial beam size increases as the output beam angle becomes large. Figure 7(c) shows the optical power efficiencies of the beam steering lens. The minimum efficiency at the maximum output beam angle was bout 0.8 (-2dB). Note that

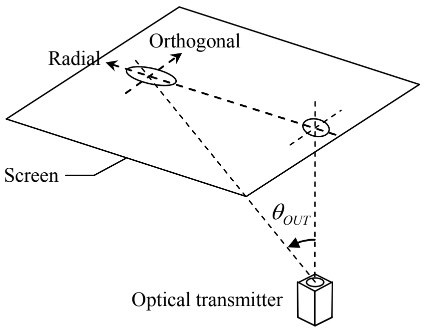


Figure 6. Experimental setup.

the sidelobes of the beam were included in the measured power, and the actual efficiencies were possibly smaller than the results in Fig. 7(c).When we assume that the received optical power is in proportion to the beam area, the optical power variation at the receiver introduced by the beam steering optics is about 13dB, which can be tolerated by the dedicated CMOS imager by a gain control of the photoreceiver circuits. In conclusion, the experimental results showed that the prototype beam steering optics operated successfully.

5. CONCLUSIONS AND FUTURE ISSUES

We described a new indoor optical wireless LAN system with dedicated CMOS imagers, which offers location-aware visually-intuitive wireless communications, wavelength- or space-division-multiplexing high-speed data transfer, and compact hardware. We demonstrated and characterized a wide-angle beam steering optics with a beam steering lens for amplifying the output beam angle. A prototype beam steering lens optimized for a near-infrared wavelength of 850 nm was fabricated. Experimental results showed that the maximum output beam angle was about ±60 degrees, which was enable to cover a 5m-by-5m room (for the ceiling 2.0 m above the nodes), and the optical power efficiency was larger than 0.8. The received optical power variation caused by the power efficiency fluctuation and the beam distortion was roughly estimated to be 13dB, which was tolerated by the dedicated CMOS imager.

In the future works, modulation of the laser intensity for data transfer and wavelength multiplexing will be introduced to the optical transmitter, and the dedicated CMOS imager will be incorporated in the communication module after functional testing.

6. ACKNOWLEDGMENTS

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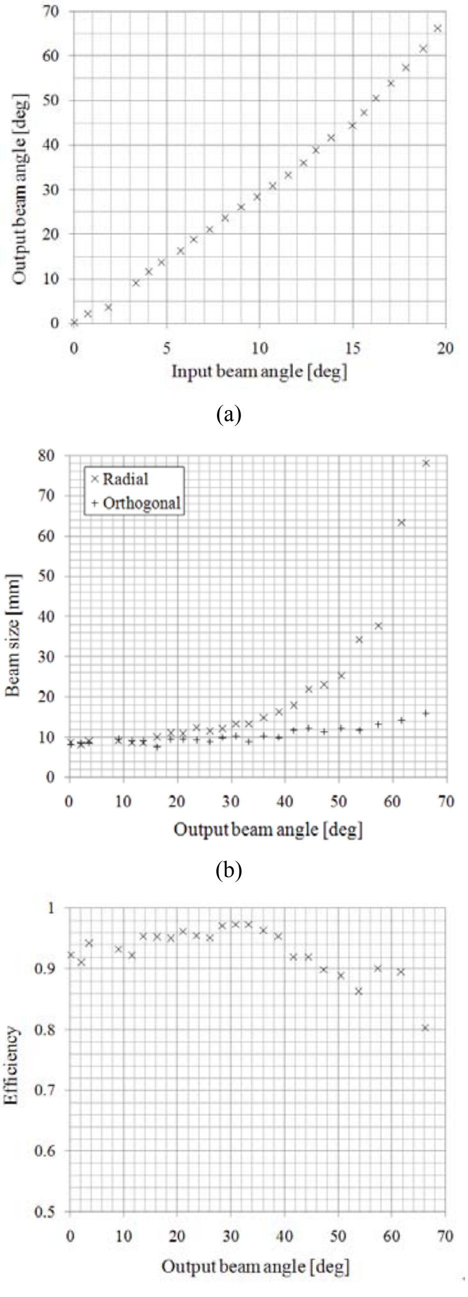

(a)

(b)

(c)

Figure 7. Experimental results of the scan lens: (a) relationship between input and output beam angles, (b) beam sizes on the ceiling, and (c) power efficiency.

7. REFERENCES

[1] Jahns, J. 1994 Optical computing hardware. Academic Press, Boston.

[2] Barry J. R. 1994. Wireless Infrared Communication. Kluwer Academic Publishers, Norwell.

[3] O'Brien, D. C., Faulkner, G. E., Zyambo, E. B., Jim, K., Edwards, D., Stavrinou, P., Parry, G., Bellon, J., Sibley, M. J., Lalithambika, V. A., Joyner, V. M., Samsudin, R. J., Holburn, D. M., and Mears, R. J., "Integrated transceivers for optical wireless communications," IEEE J. Sel. Top. in Quantum Electron., Vol. 11, No. 1, 2005, 173-183.

[4] Nonaka, K., Isobe, Y., and Tachibana, M., "Optical Micro-cell System：Smart Optical Wireless Access Data-Communication for Moving User Terminals," Jpn. J. Appl. Phys., Vol. 45, 2006, 6762-6766.

[5] Kagawa, K., Nishimura, T., Hirai, T., Yamasaki, Y., Ohta, J.. Nunoshita, M., and Watanabe, K, "Proposal and preliminary experiments of indoor optical wireless LAN based on a CMOS image sensor with a high-speed readout function enabling a low-power compact module with large uplink capacity," IEICE Trans. Comm.,Vol. E86-B, No. 5, 2003, 1498-1507.

[6] Fossum, E. R., "CMOS image sensors: electronic camera-on-a-chip," IEEE Trans. Electron. Devices, Vol. 44, No.10, 1997, 1689-1698.

[7] Fujiuchi, A., Ikeuchi, T., Kagawa, K., Ohta, J., and Nunoshita, M., Free-space wavelength-division-multiplexing optical communications using a multi-channel photoreceiver. In Proceedings of Int'l Conf. Optics & Photonics in Technology Frontier (ICO), (Chiba, Japan, 2004) 480-481.

[8] Petersen, K. E., "Silicon torsional scanning mirror," IBM J. Res. Dev., Vol. 24, No. 5, 1980, 631-637.

[9] Miyajima, H., Asaoka, N., Arima, M., Minamoto, Y., Murakami, K., Tokuda, K., and Matsumoto, K., "A durable, shock-resistant electromagnetic optical scanner with polyimide-based hinges," J. Microelectromechanical Systems, Vol. 10, No. 3, 2001, 418-424.

[10] Kawakami, T., Kagawa, K., Nishimura, T., Asazu, H., Ohta, J., Nunoshita, M., and Watanabe, K., Design of a two-dimensional scan lens for infrared wireless communications and its application to establishing a data path. In Proceedings of 28th Kogaku Symposium (Tokyo, Japan, 2003), 101-102.

[11] Miyawaki, T., Kagawa, K., Nagahata, I., Nunoshita, M., Nagahata, I., Nunoshita, M., and Ohta, J., A custom CMOS imager for wavelength-multiplexed indoor optical LANs. In Proceedings of 2007 Intl. Image Sensor Workshop (Ogunquit, USA, 2007), 124-128.

[12] Razavi B. 2003. Design of Integrated Circuits for Optical Communications, McGraw-Hill, Boston.

[13] Chen, W., Cheng, Y., and Lin, D., "A 1.8-V 10-Gb/s fully integrated CMOS optical receiver analog front-end," IEEE J. Solid-State Circuits, Vol. 40, No. 6, 2005, 1388-1396.

[14] Smith, W. J. 2000. Modern optical engineering 3rd edition, SPIE Press, McGraw-Hill, New York, 468-470.

[15] Miyawaki, T., Kagawa, K., Tanaka, E., Yamagata, M., Tanaka, Y., Nunoshita, M., and Ohta J., A wide-angle beam steering lens for 850-nm-band wavelength-multiplexed indoor optical wireless LAN. In proceedings of Optics & Photonics Japan 2007 (Osaka, Japan, 2007) 410-411 (in Japanese).

[16] Kagawa, K., Miyawaki, T., Ohta, J., Nunoshita, M., and Tanida, J., Wide-angle beam scan lens for indoor wireless optical wireless LAN. In proceedings of 6th Intl. Conf. On Optics-Photonics Design & Fabrication (Taipei, Taiwan, 2008) 297-298.