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Non Mechanical Compact Optical Transceiver for Wireless Communications with a VCSEL Array

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1. Introduction

The advantages of optical communications as compared to radiowave (RF) communications include a wider bandwidth, a larger capacity, lower power consumption, more compact equipment, greater security against eavesdropping, better protection against interference, and the absence of regulatory restrictions (Hyde & Edelson, 1997). Moreover, the demand for high-data-rate transmission from spaceborne observation platforms is steadily increasing (Toyoshima, 2005a). Free-space optical (FSO) communications systems are expected to play an important role in providing such high-data-rate communications, and optical technologies for satellite networks are expected to revolutionize space system architecture (Chan, 2003). However, maintaining a line of sight between transceivers is particularly difficult because of the small divergence angle of the laser beams. Thus, minimizing the requirements for the tracking system and ensuring the steady operation of the onboard optical terminal are important for the realization of commercial applications.

Optical terminals tend to have a large mass because optical tracking systems need to have mechanically movable parts for coarse laser pointing and tracking. Reductions in the mass, power, and volume can decrease the interference to the other missions on the satellites. Non-mechanical movable architecture is very attractive for the robust and lifelong operation of the optical terminal in orbit. The small satellite community still uses 9.6-kbps communication links by employing ham radio communications because of resource constraints in the nano-class satellites (Nakaya et al., 2003; Miyashita et al., 2006). The compact terminal can be used in nano-class satellites that have a mass of the order of a few tens of kilograms. In addition, there is a significant advantage with regard to the frequency-licensing problems faced by satellites, and the optical frequency carrier will be very useful to the small satellite community.

In this chapter, a non-mechanical compact laser communications terminal is proposed for future applications. A laser beam is transmitted by selecting the laser pixel corresponding to the direction of the optical signal received from the counter terminal. The beams are not deflected by a mechanical mirror. Instead, they are turned on and off one after the other in accordance with the direction from which optical signals are received. Multiple-input multiple-output operation is possible in this configuration. The non-mechanical transceiver can facilitate a reduction in the size of the optical system. This chapter presents the basic concept of a non-mechanical compact transceiver with a two-dimensional laser array for optical wireless communications.

2. History of optical space communications

In Japan, the National Institute of Information and Communications Technology (NICT, formerly CRL) performed the first bidirectional laser communication by using the laser communications equipment (LCE) on Engineering Test Satellite VI (ETS VI), which was launched in August 1994. Due to the failure of its apogee engine, it was injected into an elliptical orbit, and it never reached the geostationary earth orbit (GEO). Nevertheless, both uplink and downlink transmissions at wavelengths of 0.514 and 0.830 μm, respectively, and a data rate of 1 Mbps were demonstrated (Arimoto et al., 1995). In 1995, the Jet Propulsion Laboratory (JPL) and NICT conducted a ground-to-space optical communications demonstration called the Ground-to-Orbit Lasercom Demonstration (GOLD) (Wilson et al., 1998).

The European Space Agency (ESA) conducted the Semiconductor Laser Intersatellite Link Experiment (SILEX) using laser communications terminals designed for 50-Mbps LEO-GEO intersatellite link (ISL) applications. A SILEX demonstration conducted in November 2001 that linked the SPOT-4 satellite to the Advanced Relay Technology Mission Satellite (ARTEMIS) marked the first transmission of an image at 50 Mbps over a laser link (Nielsen et al., 2002). A ground-to-ARTEMIS optical communications experiment was successfully conducted in November 2001 from the ESA's optical ground station in Tenerife, Spain (Reyes et al., 2003). In September 2003, optical acquisition, tracking, and communication tests between ARTEMIS in orbit and the Laser Utilizing Communications Equipment (LUCE) engineering model on the ground, which was developed for the Optical Inter-orbit Communications Engineering Test Satellite (OICETS, or "Kirari" in Japanese), were successfully performed. The compatibility of their optical interfaces had been tested before the launch of OICETS (Toyoshima et al., 2005b).

The acquisition and tracking of satellites are problematic because of their high angular velocity. In the Strategic Defense Initiative Organization's (SDIO) Relay Mirror Experiment (RME) in the early 1990s, three laser beams (two argon-ion laser beams at 0.488 and 0.514 μm and a Nd:YAG laser beam at 1.06 μm) were projected from two ground sites at the U.S. Air Force Maui Optical Station (AMOS) in Hawaii. These beams were retroreflected and reflected from the RME satellite at 350 km. A distortion in the uplinked beam intensity profile at the satellite was reported, but information on the optical communication was not mentioned (Lightsey et al., 1994). In 2000, the Ballistic Missile Defense Organization (BMDO) developed laser communications terminal equipment for the Space Technology Research Vehicle 2 (STRV2) experiment onboard a LEO satellite. However, due to a large attitude error in the host satellite, the experiment failed (Kim et al., 2001).

OICETS was launched by a Dnepr launch vehicle from the Baikonur cosmodrome in the Republic of Kazakhstan and placed in a LEO at 610 km with an inclination of 97.8°. The functioning of the satellite's systems was checked for the first three months, and during this time, stars and planets were acquired and tracked. In December 2005, the demonstration of the first bidirectional laser communication between OICETS and ARTEMIS was successfully conducted with a return link of 50 Mbps and a forward link of 2 Mbps (Jono et al., 2006; Takayama et al., 2007; Toyoshima et al., 2006; Toyoshima et al., 2007). Following these intersatellite experiments, the Kirari optical communication demonstration experiments were conducted by using the NICT optical ground station (KODEN) in collaboration with the Japan Aerospace Exploration Agency (JAXA) in March, May, and September 2006. Thus, the ground-to-OICETS laser communication experiment was the first in-orbit demonstration using a LEO satellite.

In March 2008, a 5.5-Gbps intersatellite optical communication link was successfully tested by using German laser terminals; this data rate is the fastest in space-borne communications to date. The laser terminals were tested in space for broadband data transmission between two satellites, the German satellite TerraSAR-X and the U.S. satellite NFIRE. Optical intersatellite links were established for a range of approximately 5000 km and were operated flawlessly at a data rate of 5.5 Gbps in both directions.

Through the research and development for FSO communications conducted in NICT, it is considered that a compact communications terminal will have applicability in FSO communications in the future. In this paper, we propose the concept of a compact free-space laser communications terminal with a vertical-cavity surface-emitting laser (VCSEL) array. There are no mechanically moving parts in this optical system. This compact terminal can receive optical communications signals from multiple platforms and can transmit multiple optical communications beams to the counter terminals. Therefore, such an optical system can serve as a multiple-input multiple-output (MIMO) system.

3. Conceptual terminal design

3.1 System Configuration

Figure 1 shows the configuration of the proposed compact laser communications transceiver. The laser beam from the counter terminal passes through the telescope lens, is reflected from the beam splitter and is detected by the CCD sensor. The CCD sensor detects the direction of the line of sight of the counter terminal, and one of the array lasers is selected according to the direction of the signal received by the CCD. A CCD with a pixel size equal to that of the XGA (1280 × 1024) is used. The centroid of the pixels is calculated in the computer, and the laser beam corresponding to the direction of the centroid is turned on. Figure 2 shows the photograph of the manufactured compact laser communications transceiver and the control computer system. With this configuration, multiple inputs from multiple platforms can possible with the parallel laser spot detection processing, and the MIMO configuration can be possible as well (Short et al., 1991).

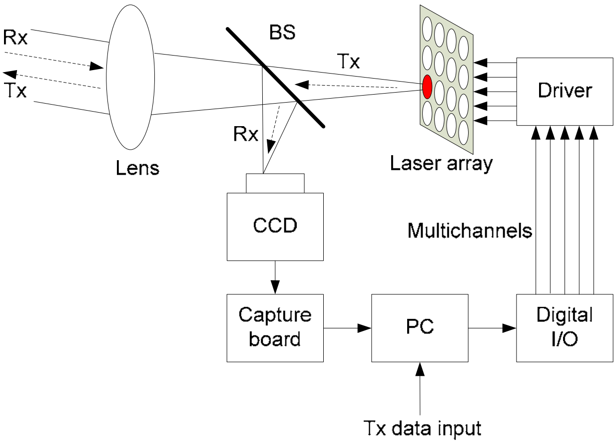

Fig. 1. Configuration of the proposed compact laser communications transceiver

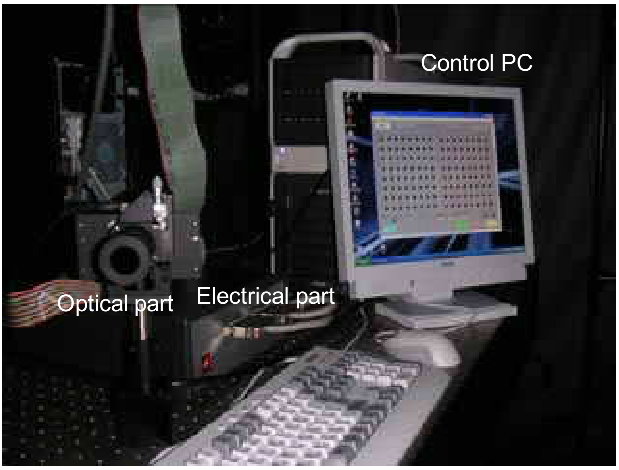

Fig. 2. Photograph of the manufactured compact laser communications transceiver

3.2 Optical part of the transceiver

The laser beam is transmitted from the two-dimensional laser array through the beam splitter and the telescope lens. The laser beam is selected by the centroid calculation in the computer. The beam divergence angle of the selected laser beam covers the angular interval between adjacent laser arrays (Cap et al., 2007). Two adjacent laser beams are turned on simultaneously to ensure that the laser transmission is not interrupted and to maintain a constant optical intensity at the counter terminal. Figure 3 shows the beam transmission configuration for a two-dimensional laser array. With this transmission method, the transmitted laser beam is not interrupted during the tracking of the counter terminal. Each laser beam is combined by an interval at the half width at half maximum (HWHM). Therefore, if the two adjacent laser beams are turned on simultaneously, the optical intensity can be almost constant at the counter terminal.

For the transmitter, we use an 8 × 8 VCSEL array, as shown in Figure 4, for the first evaluation model. We choose a VCSEL because it is easy to arrange it in an array, there is no mechanical part, and it is readily available. The maximum output power of one pixel is 4 mW at a wavelength of 850 nm as shown in Table 1. The laser diode can be modulated at above 2.5 GHz. An example of the beam pattern is measured by a beam profiler at 30 cm distance from the compact laser communications transceiver as shown in Figure 5. All the VCSELs could be turned on individually. The beam pattern from the VCSEL used here exhibits a donuts mode instead of the Gaussian one. The beam divergence for this evaluation model was designed to be 2 degrees for one VCSEL, which is more broadened beam divergence than that of the real system because the number of the VCSEL array is not enough. As shown in the next subsection, a large number of pixels are required depending on the angular coverage of the transmitter.

Parameter	Value
Number of the array	64 (8 × 8)
Maximum output power of one pixel	4 mW
Wavelength	850 nm
Beam divergence angle	20-30 degrees
Minimum frequency response	2.5 GHz

Table 1. Specification of the VCSEL array

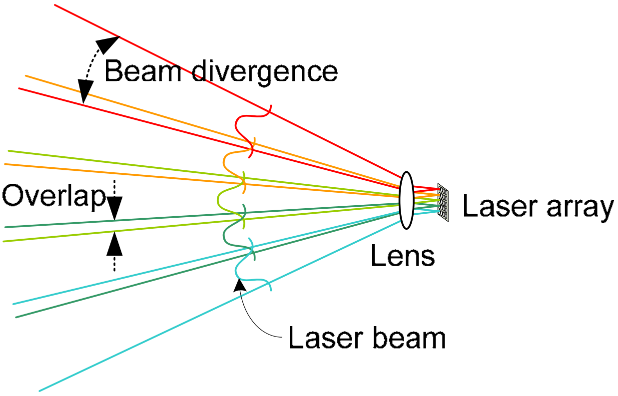

Fig. 3. Laser beam transmission method

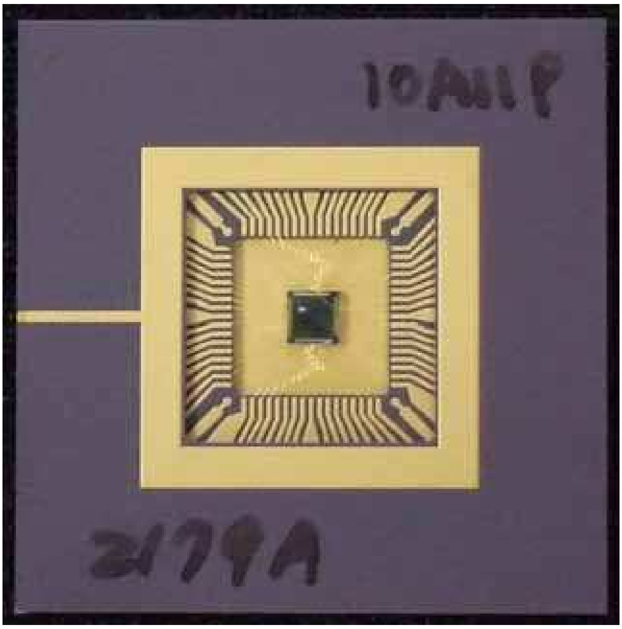

Fig. 4. Photograph of the 8 × 8 VCSEL array

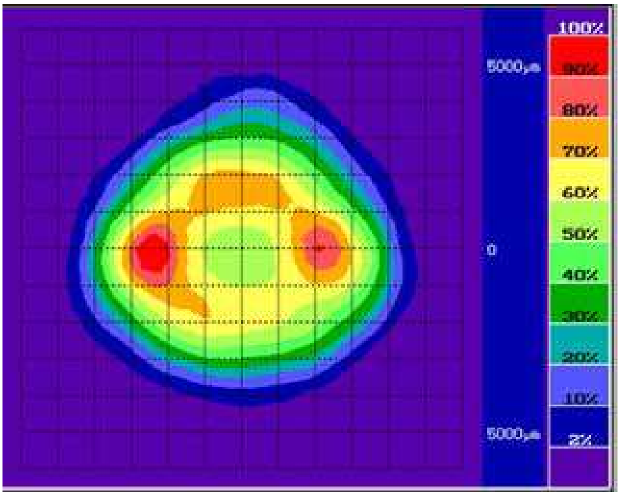

Fig. 5. Example of the beam pattern measured at 30 cm distance from the compact laser communication transceiver

Figure 6 shows the optical part of the manufactured compact laser communications transceiver. The small telescope consists of 9 lenses. The VSCEL is mounted at the end of the small telescope and the CCD sensor is mounted on the upper side of the telescope as shown in Figure 6. The size of the optical part of the telescope (lens mount) is 13.5 × 6 × 11 cm, and the mass is 1 kg as shown in Table 2.

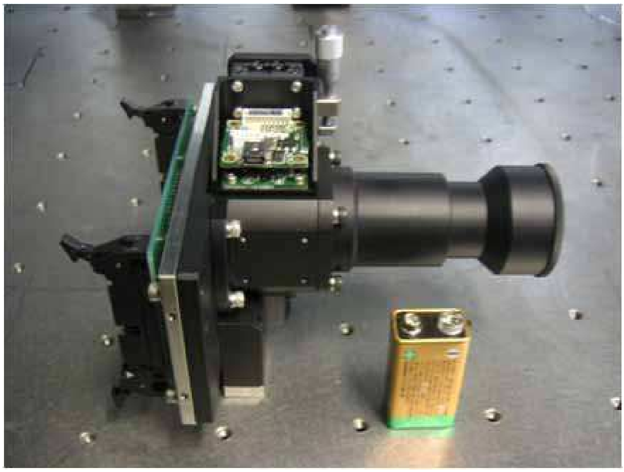

Fig. 6. Optical part of the compact laser communication transceiver

Fig. 7. Electrical part of the compact laser communication transceiver

Resource		Value
Optical part	Mass	1 kg
	Size (lens mount)	15 × 12 × 12 cm (13.5 × 6 × 11 cm)
Electrical part	Mass	3.1 kg
	Size	27 × 26 × 10 cm
	Power	< 10 W

Table 2. Resources of the compact laser communication transceiver

3.3 Electrical part of the transceiver

Laser beams in the VCSEL array are modulated according to the received laser spot extracted by the control computer system as shown in Figure 1. Two 32-channel digital I/O boards are installed and can transmit the data at a data rate of 25 Mbps. Figure 7 shows the photograph of the electrical part of the manufactured laser driver. The electrical part as shown in Figure 7 can drive 64 channels of the VCSEL by the selected signal from the digital I/O boards. The laser diode is driven at an average power of 2 mW by the driver electronics. The electrical part of the compact laser communications transceiver has the mass of 3.1 kg, the size of 27 × 26 × 10 cm, and the power consumption of less than 10 W as shown in Table 2.

Parameters	Unit	Uplink	Downlink
TX power	W	1.00	0.002
	dBm	30.0	3.0
Pixel size of laser array	-	-	1024 × 1024
Beam diameter at telescope	cm	72.1	0.125
Pointing error	μrad	23.1	0.0
TX beam divergence (FWe^{2}M)	μrad	1000.0	869.3
Angular coverage (FWHM)	degree	0.06	60.0
TX optic loss	dB	–2.0	–2.0
Wavelength	m	8.15E–07	8.50E–07
Average pointing loss	dB	0.0	0.0
TX gain	dB	72.0	76.3
Distance	m	1.00E+06	1.00E+06
Space loss	dB	–263.8	–263.4
Atmospheric transmission	dB	-6.0	–6.0
RX antenna diameter	cm	3.0	150.0
RX gain	dB	101.3	134.9
RX optic loss	dB	–2.0	–2.0
RX power	dBm	–70.5	–59.2
Data rate	bps	1.00E+05	1.00E+06
Sensitivity (@BER of 10^{-6})	Photons/bit	2200	2200
	dBm	–72.7	–62.9
Link margin	dB	2.2	3.6

Table 3. Link budget analysis of an optical communication link between a ground station and a satellite

3.4 System analysis

Table 3 summarizes the results of the link budget analysis for the proposed compact optical transceiver. The optical link is designed to connect an optical ground station to a LEO satellite. The output laser power for a pixel of the VCSEL array is assumed to be 2 mW at 850 nm wavelength. The beam divergence angle is set at 869 μrad for a single laser pixel for the full width at $1/e^2$ maximum (FWe^2M), and the angular coverage of the transmitter is 60° for a 1024 × 1024 array, which is enough to cover the attitude error of the satellites. The overlap of the beams is set to occur at the HWHM. The beam pointing error can be considered as zero because the transmitting power can be doubled by turning on the adjacent two VCSELs simultaneously. The beam diameter of the transmitter is 1.25 mm. The link distance is assumed to be 1000 km from the optical ground station to the LEO satellite. If we use a receiving telescope with a 1.5-m diameter, the link margin will be 3.6 dB at a data rate of 1 Mbps. The data rate is rather lower as compared with that of a trunk optical communications line; however, some nano-class satellites still use a data rate of the order of 1.2 k to 9.6 kbps (Nakaya et al., 2003; Miyashita et al., 2006). Despite the low data rate, this system is advantageous because it overcomes the frequency-licensing problem of the satellites. The compact optical transceiver can be used in such the nano-class satellite community for space communications in the future.

Table 4 tabulates the results of the link budget analysis for a horizontal terrestrial optical communication link on the ground. By using the proposed non-mechanical compact transceiver, a data rate of 1 Gbps can be realized for a distance up to 1 km with an angular coverage of 60°. The diameter of the receiver aperture is 5 cm in this case. If a receiver aperture with a diameter of 3 cm is used, a data rate of 1 Gbps can be realized for a distance up to 700 m. As shown in Table 4, the proposed non-mechanical method can be applied to terrestrial free-space laser communications. If the proposed terminal can be made very compact, mobile users can use the high-data-rate optical link without the mechanical tracking system on the ground, like a digital camera. Setting up the optical transceivers is easy and their installation is not complicated. In the future, the applicable fields for the optical transceivers will include not only satellite communications but also high-speed cell phone communications, wireless LAN, mobile communications, and building-to-building fixed high data rate communications without any difficulties.

4. Conclusion

A non-mechanical and very compact optical transceiver has been presented. A VCSEL array is used in the transceiver, and the laser pixel that is turned on depends on the direction of the counter terminal from which the CCD receives a signal. The mass, volume, and power of the proposed system can be reduced because it contains no mechanically movable structures. In this study, an 8 × 8 VCSEL has been used. The angular coverage of the optical terminal can be extended if a larger number of pixels are used. As there are no regulatory restrictions on the use of the optical frequency, the proposed compact laser communications transceiver will be useful for downloading data from nano-class satellites in future applications.

Parameters	Unit	Horizontal link
TX power	W	0.002
	dBm	3.0
Pixel size of laser array	-	1024 × 1024
Beam diameter at telescope	cm	0.125
Pointing error	μrad	0.0
TX beam divergence (FWe^{2}M)	μrad	869.3
Angular coverage (FWHM)	degree	60.0
TX optic loss	dB	–2.0
Wavelength	m	8.50E–07
Average pointing loss	dB	0.0
TX gain	dB	76.3
Distance	m	1.00E+03
Space loss	dB	–203.4
Atmospheric transmission	dB	–6.0
RX antenna diameter	cm	5.0
RX gain	dB	105.3
RX optic loss	dB	–2.0
RX power	dBm	–28.8
Data rate	bps	1.00E+09
Sensitivity (@BER of 10^{-6})	photons/bit	2200
	dBm	–32.9
Link margin	dB	**4.1**

Table 4. Link budget analysis of a horizontal terrestrial laser communication link on the ground

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Mobile and Wireless Communications Network Layer and Circuit Level Design

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Mobile and wireless communications applications have a clear impact on improving the humanity wellbeing. From cell phones to wireless internet to home and office devices, most of the applications are converted from wired into wireless communication. Smart and advanced wireless communication environments represent the future technology and evolutionary development step in homes, hospitals, industrial, vehicular and transportation systems. A very appealing research area in these environments has been the wireless ad hoc, sensor and mesh networks. These networks rely on ultra low powered processing nodes that sense surrounding environment temperature, pressure, humidity, motion or chemical hazards, etc. Moreover, the radio frequency (RF) transceiver nodes of such networks require the design of transmitter and receiver equipped with high performance building blocks including antennas, power and low noise amplifiers, mixers and voltage controlled oscillators. Nowadays, the researchers are facing several challenges to design such building blocks while complying with ultra low power consumption, small area and high performance constraints. CMOS technology represents an excellent candidate to facilitate the integration of the whole transceiver on a single chip. However, several challenges have to be tackled while designing and using nanoscale CMOS technologies and require innovative idea from researchers and circuits designers. While major researchers and applications have been focusing on RF wireless communication, optical wireless communication based system has started to draw some attention from researchers for a terrestrial system as well as for aerial and satellite terminals. This renewed interested in optical wireless communications is driven by several advantages such as no licensing requirements policy, no RF radiation hazards, and no need to dig up roads besides its large bandwidth and low power consumption. This second part of the book, Mobile and Wireless Communications: Key Technologies and Future Applications, covers the recent development in ad hoc and sensor networks, the implementation of state of the art of wireless transceivers building blocks and recent development on optical wireless communication systems. We hope that this book will be useful for students, researchers and practitioners in their research studies.

How to reference

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