Contribution to the achievement of SDGs
by Furukawa Electric Group

Demonstration of Highly Reliable Si-Photonics-Based In-Vehicle Optical Network (SiPhON) for Autonomous Driving

Daisuke Noguchi[*1], *Masayuki Iwase*[*1], *Masahito Morimoto*[*1], *Keisuke Kawahara*[*1], *Masato Shiino*[*1], *Yuka Sawada*[*1], *Hitoshi Shimanuki*[*1], *Hironobu Yoshida*[*1], *Satoru Torimitsu*[*2], *Keisuke Oishi*[*2], *Kei Takahashi*[*2], *Kei Ishikawa*[*3], *Minoru Morita*[*4]

ABSTRACT In the automotive industry, the technological innovation in the architecture of in-vehicle communication has been advancing for conversion to autonomous driving. It is required for the autonomous driving vehicle to equip in-vehicle networks capable of increasing electronics devices of sensors, which has not only high capacity and low delay but also high performance in Electromagnetic Compatibility (EMC). The application of optical communication technology can be proposed to satisfy these requirements. However, we may have problems of deteriorating the reliability of the system when applying light emitting devices in the severe automotive environment. To solve this problem, in our Silicon-Photonics based in-vehicle Optical Network (SiPhON) system, Distributed Feedback (DFB) lasers as light sources are independently arranged and the silicon photonics devices in which optical modulators and optical detectors are linked in a ring system. We have demonstrated that high speed communication is feasible in our system by multistage series connection of independent Continuous Wave (CW) optical sources and optical modulators.

1. INTRODUCTION

Recently in the automotive industry, a once-in-a-century technological innovation as symbolized by Connected, Autonomous, Share and Service, Electric (CASE) has been advancing. Automobiles are driven by electric power and controlled by electronics and the autonomous driving is realized by sensors such as cameras, Light Detection and Ranging (LiDAR), radars and recognition and judgment by Artificial Intelligence (AI). Moreover, constantly connecting to cloud networks like smart phones, it is getting practicable always to pass information to and from the network and update software. Accompanied by the evolution of automobiles, technical innovation is required in communication architecture. Transition of in-vehicle communication architecture is shown in Figure 1.

Figure 1 (a) shows a traditional configuration called flat type. There were tremendous number of wire harnesses stretched in every direction in a vehicle under no concept of efficiently connecting Electrical Control Units (ECUs) to each other. Today when electronic control of a vehicle is advanced, networks developed for in-vehicle use are introduced in a vehicle and the communication architecture has transited to a domain type shown in Figure 1 (b). The processing in each domain is controlled by a Domain Controller and communication among each domain is operated through Gateway. Applying the domain type architecture enabled the whole network in a vehicle work in concert with each other. However, the cost and weight of the wire harnesses cannot be ignored, because the total length of wire harnesses connecting equipment in a vehicle is still long. In advanced autonomous driving in future, electronic devices and equipment such as sensors and cameras are increasing furthermore, therefore we are aiming at the zone type architecture shown in Figure 1 (c) in which sensor information on the network in a vehicle is gathered and transmitted through a core network to a central computer. The communication capacity for advanced autonomous driving will exceed 100 Gbps as shown in Table 1.

Furthermore, EMC requirements for electric vehicles are severe and an electromagnetic shield cable is necessary because electric circuits are easily influenced by the electromagnetic field. Electromagnetic shield cable has problems in weight and flexibility also. And, in a main line in which its propagation distance is as long as several

[*1] Electronics Laboratory, Research & Development Division
[*2] Sustainable Technology Laboratory, Research & Development Division
[*3] Photonics Laboratory, Research & Development Division
[*4] AT Development Department, AT & Functional Plastics Division

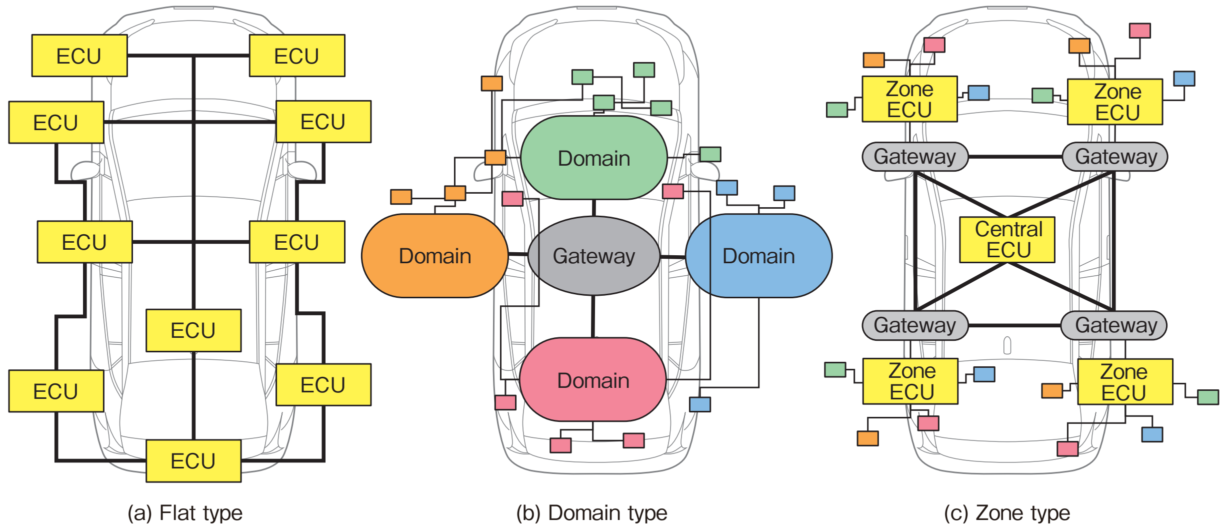


Figure 1 Transition of an in-vehicle communication architecture.

Table 1 Transmission capacity required for autonomous driving.

Required Communication Capacity		
4K Camera	>10 Gbps	X 5–12
LiDAR	>1 Gbps	X 2–6
RADAR	>100 Mbps	X 4–10
Cellular, Connected	>10 Gbps	
Infotainment	>100 Mbps	

meters, the propagation loss is so serious to make it difficult to expand the bandwidth. Recently, to solve these problems, a lot of researches have been done in applying optical communication technology to vehicles.

We have 25/50G BASE-AU (IEEE802.3cz, Multi-Gigabit Optical Automotive Ethernet, called OMEGA)[1] as an existing standard for optical network in a vehicle corresponding to the requirements mentioned above. In OMEGA, Vertical Cavity Surface Emitting Laser (VCSEL) with 980 nm as a central wavelength is applied as a light emitting device. However, as the reliability of the system will be a problem when multiple VCSELs are mounted in the severe automotive environment, we have proposed a new communication architecture[2)-7)] based on the silicon photonics technology.

2. CONCEPT OF THE SiPhON SYSTEM

The SiPhON system is such a system in which CW lasers are independently distributed and silicon photonics devices are integrated with optical modulators and detectors are linked in a ring shape to communicate with each other. Silicon photonics is a technology where optical waveguides and electronics circuits are integrated into a silicon substrate to be an innovative technology equipped with both high speed and large capacity transmission and power savings. The conceptual diagram of the SiPhON system configured with MASTER device and Gateway devices is shown in Figure 2.

The Gateway devices become an interface for sensors

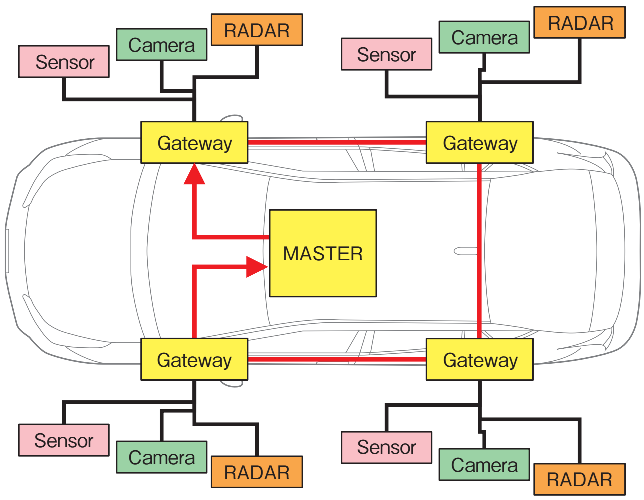


Figure 2 Conceptual diagram of the SiPhON system.

distributed in each zone when a vehicle body is divided into zones for its areas. Signals integrated in each zone circulate in a ring shape optical network to reach the MASTER device.

2.1 Configuration of Devices

The configuration of MASTER device and Gateway devices in the SiPhON system is shown in Figure 3.

There are control planes (C-planes) to transmit a synchronizing signal and data planes (D-planes) which have no more than 10 Gbps transmitting capacity in the SiPhON system. Each device is controlled by Field Programmable Gate Array (FPGA) and the MASTER device has CW light sources, optical detectors integrated with Mach-Zender (MZ) type optical modulators and optical switches, and optical detectors for receiving optical signals. The DFB laser is adopted as the CW light source, and the MASTER device has a function to switch over to the redundant system by optical switches. The Gateway device has Modulator and Detector (MD) optical circuits. The MD optical circuit is a device integrated with Modulators and Detectors. Here, when the MASTER device transmits signals to any of the Gateway devices,

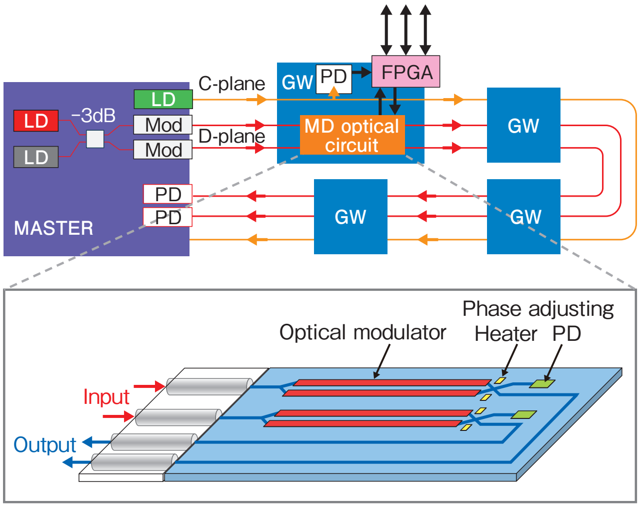


Figure 3 Configuration of devices.

the MASTER device transmits modulated optical signals modulated by an MZ type optical modulator in it. The Gateway device for receiving signals receives signals through Photo Diodes (PDs) integrated into the silicon photo device. The other Gateway devices hand the modulated light signals over to the next Gateway device without any changes. When any Gateway device transmits signals, the Gateway device modulates the CW light given by the MASTER device through its modulator to let the modulated optical signals circulate in the ring shape optical network and an optical detector in the MASTER device receives the signals. In this development, we have achieved the theoretical examination based on the condition that 10 Gbps for data signals on the D-plane and 1.25 Gbps for synchronizing signals on the C-plane.

2.2 MD Optical Circuits

We explain specific contents of the optical circuit. The MD optical circuit is integrated with the MZ type optical modulators and PDs and either transmit signals or receive signals in this single device. The MD optical circuit has 2 channels for each of optical modulators and PDs to secure redundancy. Here, the MD optical circuit can change the extinction characteristic according to the combination of a pair bias value (2 values: High/Low) and using this change of extinction characteristic, selects three-mode operation based on voltage control. A conceptual diagram of the three-mode operation by the MD optical circuit is shown in Figure 4.

(1) A Gateway device suppresses the attenuation of optical power to hand the optical signals to the next Gateway device: Thru operation.
(2) A Gateway device receives the optical signals transmitted from the MASTER device: Listen operation.
(3) A Gateway device modulates the CW light through the optical modulator to transmit the optical signals: Talk operation

An operation from (1) to (3) is selected according to the combination of bias values and any of the Gateway devices and the MASTER device become a transmitter and a detector respectively.

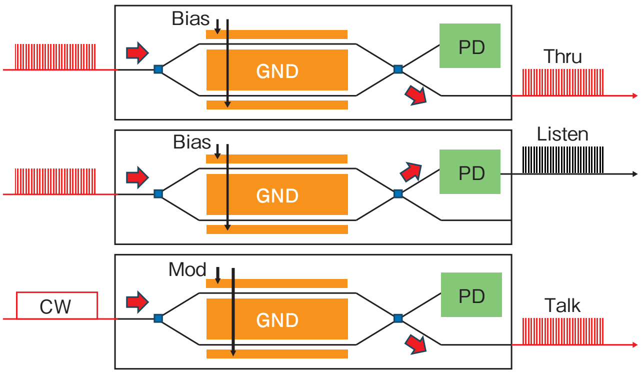


Figure 4 Three-mode operation of an MD optical circuit.

3. ADVANTAGES IN COMPARISON WITH THE EXISTING STANDARDS

We have made the advantage of our SiPhON system clear in comparison with existing automotive communication standards by computer simulation.

3.1 System Reliability

The optical signal transmission has advantages in the zone type automotive communication network from a viewpoint of EMC performance and propagation distance, and above-mentioned OMEGA is already standardized. We are going to explain the advantages of our SiPhON system in comparison with the OMEGA. In the OMEGA, topology such as a star type, a tree type and a daisy-chain type can be assumed. And we will compare the reliability of the OMEGA network equipped with five Gateway devices linked in the daisy-chain type to that of our SiPhON system equipped with the same number of Gateway devices. The daisy chain network configuration of OMEGA is shown in Figure 5 as an example.

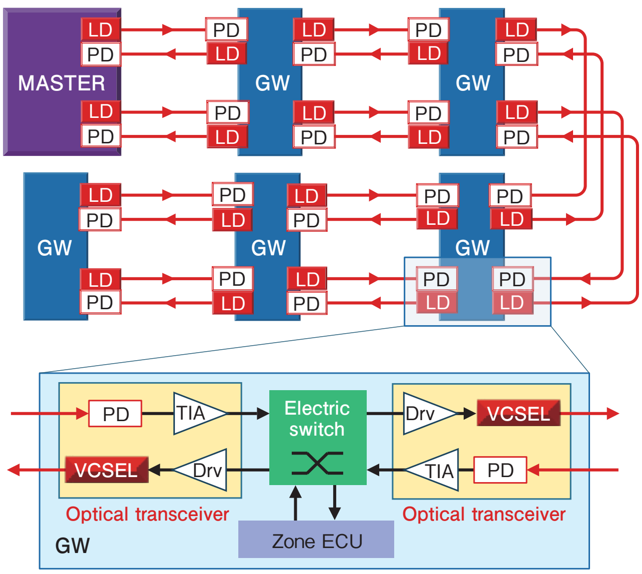


Figure 5 Daisy chain network configuration of OMEGA.

In this configuration, we assume an optical network with 2 lanes based on our consideration to maintain redundancy. At this moment, 20 VCSELs will be mounted in the whole system. It is the largest problem of the OMEGA that its reliability deteriorates along with the mounting of so many optical transceivers. In general, life of light emitting devices will be reduced by half at each time when temperature increases by 10°C, and moreover it decreases abruptly when current density increases. No less than 10 years life is already realized for the 980 nm distortion-type VCSEL applied to the OMEGA under low current operation, but its system life will be drastically shortened when mounting 20 VCSELs. And the Gateway device in the zone type architecture is required to be mounted either under roof or under hood (in engine compartment), where it is exposed to severe temperature environment, and more, its direct modulation type VCSEL has to operate in higher temperature than the ambience because of its self-generated heat. On the other hand, in the SiPhON system, DFB lasers are the only light emitting devices in the MASTER device, and the life of the laser can be extremely extended by controlling the laser to operate within a certain temperature range. Here, a line graph to compare their Mean Time-To-Failure (MTTF) which shows the average time of failure occurrence in the OMEGA system and in the SiPhON system is shown in Figure 6.

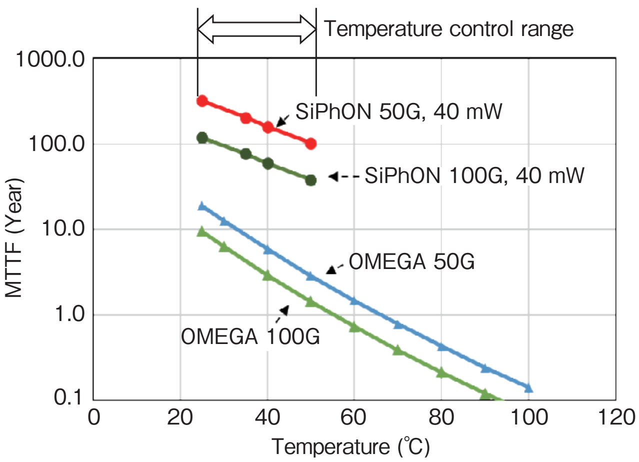


Figure 6 Comparison of MTTF of OMEGA-SiPhON.

In this graph, MTTF of SiPhON and OMEGA are compared under two conditions of transmission capacity of 50 Gbps and 100 Gbps. Under the condition of transmission capacity of 100 Gbps, the system life becomes shorter because as many as 4 of 25 Gbps light sources are required. The system life of the SiPhON can be expected to be no less than 100 years when only the operation temperature range of light sources in the MASTER device is restricted between 25°C and 50°C. On the other hand, we can see that in the OMEGA network in which 5 Gateway devices are linked in the daisy chain type, the system life does not satisfy even one year, when the ambient temperature of the Gateway devices reaches 80°C.

3.2 Low Latency Performance

Next, focusing on the low latency performance of a daisy chain type system configured in an Ethernet system against that of our SiPhON system. We have compared the image traffic latency by computer simulation when each of 6 video cameras transmits uncompressed 4K 60 p images to Dashcam.

We have examined in-vehicle communication networks with 100 Gbps circuit capacity. Comparable Ethernet network is configured according to the specification of “AVB + TSN” which is a combination of standards for image transmission, Audio Video Bridging (AVB) and low-latency clock synchronization standard, Time-Sensitive Networking (TSN). The configuration of examining Ethernet system is shown in Figure 7.

The configuration of SiPhON system in comparison is shown in Figure 8.

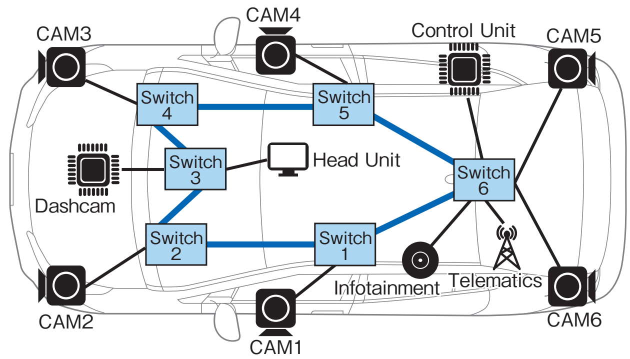


Figure 7 Configuration of an Ethernet system.

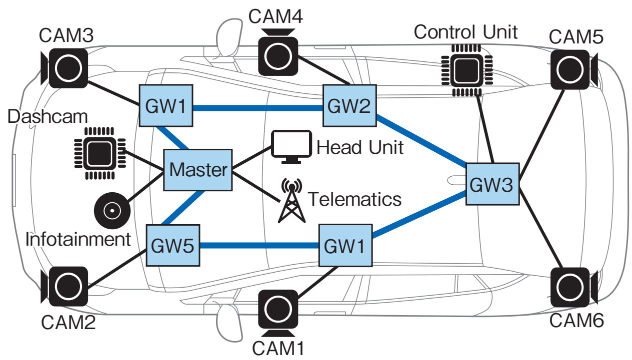


Figure 8 Configuration of the SiPhON system.

Figure 9 shows the time transition of latency of video traffic from video camera 6 to Dashcam in the Ethernet system. We had 34 μs latency minimum and 90 μs latency maximum, because 8 μs latency occurred in Ethernet switches in each zone.

Figure 10 shows the time transition of latency of video traffic from video camera 6 to Dashcam in our SiPhON system. Minimum latency was 3.5 μs and maximum latency was 12 μs between the ends. Further, applying an optimum slot share pattern to increase Talks of the Gateway with wider occupied bandwidth, we have got the prospect that 50 Gbps or more could be realized in transmission performance after confirming the capability to handle approximately 84 Gbps traffic with 2.1-3 μs latency at 9000 bytes in slot size and 100 ns guard bank.

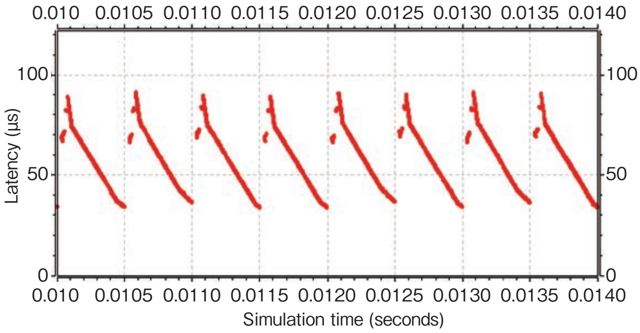


Figure 9 Time transition of delay of video traffic from video camera 6 to dashcam in an Ethernet system.

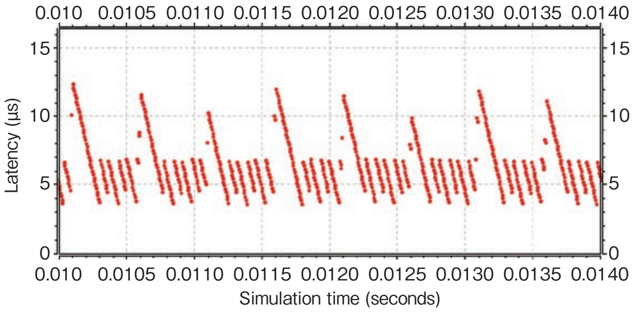


Figure 10 Time transition of delay of video traffic from video camera 6 to dashcam in a SiPhON system.

4. PREPARATION OF PROTOTYPE AND ITS EVALUATION

We have selected Low Temperature Co-fired Ceramics (LTCC) as a package to contain the MD optical circuit. The LTCC is easy for composing multi-layer structure and suitable for high density packages. Further cavities can be formed and parasitic inductance caused by wire bonding can be reduced. The structure of the MD module containing the MD optical circuit is shown in Figure 11.

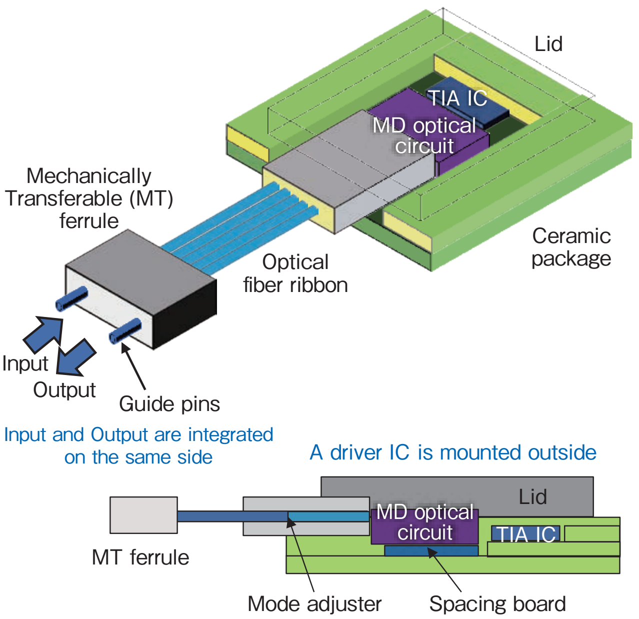


Figure 11 Structure of MD optical module.

Height of the optical axis of the MD optical circuit was adjusted using silicon substrate (300 μm in thickness) as a spacing board. Pasting die attach films together on the front and the back surface of the spacing board, we have mounted the optical circuit.

Trans Impedance Amplifier (TIA) and smoothing capacitances are contained in the optical module other than the MD optical circuits. Its optical port has 8 cores (2 cores for signal input, 2 cores for output, 4 cores for positioning) in 250 μm pitch, and single mode fibers are connected to optical waveguides in butt joint structure. The picture of a prototype of our MD optical module is shown in Figure 12.

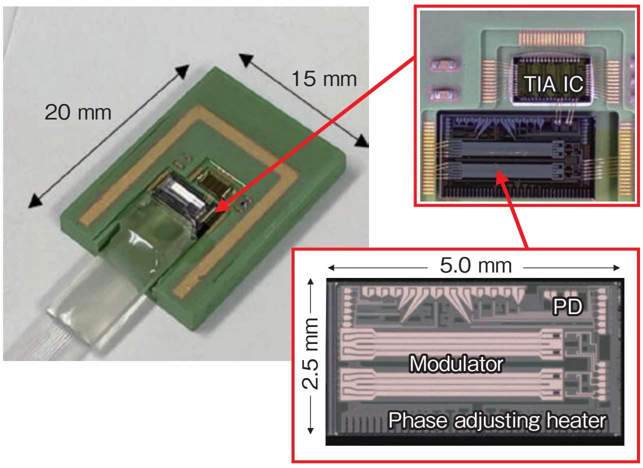


Figure 12 Picture of an MD optical module.

The MD module selects one of 3 mode operations by voltage control. It is necessary to set a pair of bias values High during Talk operation. And changing the extinction characteristic by setting one bias value Low, each one of the voltage conditions is assigned to either Listen or Thru. As it is preferable that the insertion loss keeps minimum during Thru operation, we have chosen 5.6 mA for heater current value as the adjustment point to determine each operation condition in this prototype device. The extinction characteristics of the MD optical module at each bias condition are shown in Figure 13.

In Listen operation, as extinction means an increase of the intensity of light flowing into the PD, increase and decrease of the photo current is shown in Ipd graph shown in Figure 13. We assess that the adjustment point for Talk operation conforms to the point reduced by 2 dB from the point of maximum light output and that for Listen operation conforms to the point near the point of maximum Ipd respectively. The insertion loss was –10 dB during Thru operation and the extinction ratio was 5.5 dB during Talk operation to show a good eye pattern. During Listen operation, a good eye pattern was confirmed as well even if it was output from a post amplifier. Eye waveforms during Talk operation or Listen operation are shown in Figure 14.

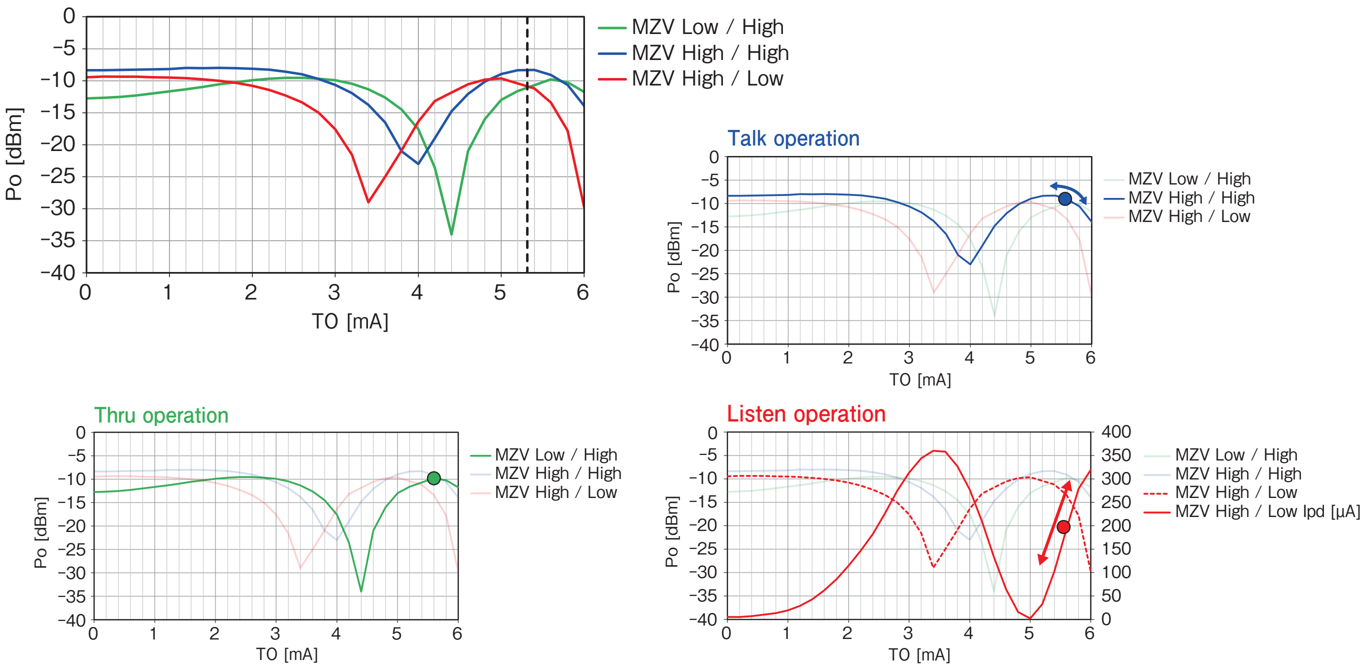


Figure 13 Extinction characteristics of an MD optical module under each bias condition.

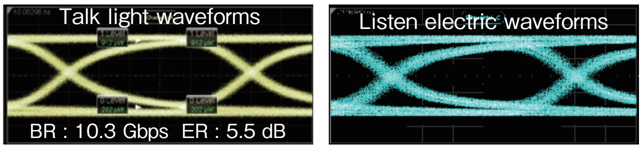


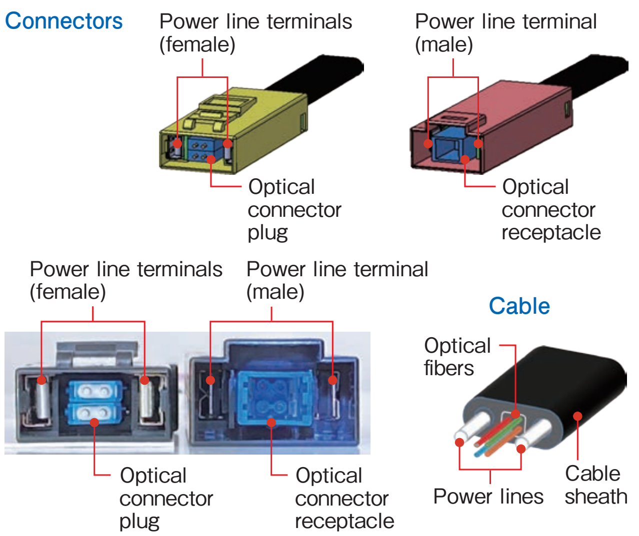
Figure 14 Eye waveforms during Talk operation or Listen operation.

Next, in our SiPhON system, optical fiber cables are required to link our prototype MD modules in a multistage link system. The optical fiber cable applied for in-vehicle use in future is required to have good reliability and environmental endurance performance as well. In addition, we have such a main purpose for this development as to reduce the cost and weight of wire harnesses. The weight of wiring systems and the number of components such as connectors have been increasing because of the growing number of sensors. The weight of the wire harness installed all over a vehicle body is as heavy as approximately 50 kg for a large-size Sport Utility Vehicle (SUV) to make up approximately 2% of its whole weight. Moreover, the number of its components reaches as many as approximately 2000 pieces. A picture of an automotive wire harness is shown in Figure 15.

Figure 15 Automotive wire harness.

The price of copper, which is the main material of wire harness has increased by almost 40% in the past 10 years and is estimated to increase still from now on, so the price of a vehicle is affected by the increase of wire harnesses. Recently, the need for the replacement with aluminum wires has been growing because aluminum wires have advantages against the global depletion of copper resources and the fluctuating prices of copper as well[8].

We have developed Flexible Automotive Signal and Power Unified Line System (FASPULS) which realizes collective connection of power wires and signal wires shown in Figure 16 for our purposes to reduce man-hour in installing wire harnesses, to simplify the wiring system and to reduce weight.



Single Mode Fiber (SMF) optical connection loss: ≦0.2 dB @1550 nm
Electric current capacity: 50A × 2

Figure 16 Signal and power unified line system harness FASPULS.

The FASPULS is capable of power supplying up to 100 A provided with 2 poles of 50 A power source. Aluminum wires are adopted for the wiring to reduce the weight. In the center of the cable, 4-lines optical fibers as communication lines are implemented. For the optical fiber wires, we have implemented Micro-Links (μlinx) Avionics Fiber Optic Cables made by OFS, which already had actual experience in the application in an aircraft field and other ones. The μlinx is designed sturdy against external forces such as tensile stress and bending stress as well because of its structure where optical fiber core wires are coated with aramid fiber reinforced members and covered with ETFE (fluoric resin) external jacket in extrusion molding. The specifications for high heat-resistant optical fiber cable μlinx are shown in Figure 17.

Its operation temperature is from −65 to 150°C to maintain a high margin far above the requirement standard for in-vehicle components. Further, we have achieved automotive reliability tests because tolerance against vibration is required in the automotive environment. Vibration test conditions (ISO16750-3) prescribed in ISO standards and a vibration test machine are shown in Figure 18.

The conditions prescribed in the automotive standard are longer in period and higher in frequency than those in Telcordia communication standard. We have confirmed that no changes were found before and after the test and the loss value was no higher than that in the loss standard.

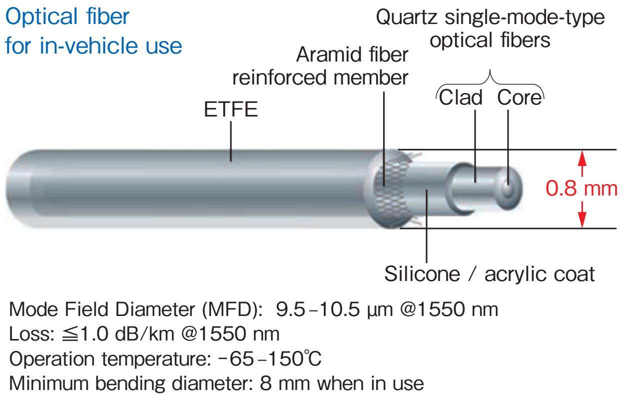
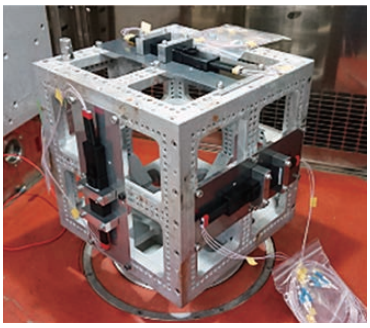


Figure 17 Specifications for high heat-resistant optical fiber cable μlinx.

	Unit	Vibration test for automotive cable ISO 16750-3	Telcordia test CR326-CORE	Reference High voltage connectors
Number of directions		3	3	3
Test period	[h]	8	2	41.2
Maximum acceleration	[m/s^2]	27.1	*	49
Minimum frequency	[Hz]	10	10	10
Maximum frequency	[Hz]	1000	55	200
Sweep			45 Hz/min	1oct/min
Load current pattern				250 A
Temperature	[℃]		23	



* 1.5 mm (peak to peak)

Figure 18 Vibration test conditions (ISO16750-3) and vibration test machine.

5. DEMONSTRATION TEST

A demonstration test was carried out in Yagami Campus Research Building of Keio University in March of 2024. The demonstration test system of the SiPhON system is shown in Figure 19. The MASTER device and 4 Gateways are linked with optical links.

Two 4K cameras, a LiDAR and a radar of a Controler Area Network (CAN) interface are linked to the Gateways through Ethernet switches and all the information is distributed to the MASTER device. We carried out a demonstration test that the virtual driving scene on Monitor A was projected to be shot by the 4K camera, and the data was transmitted from the MASTER device through the SiPhON system to a computer in which image processing such as object recognition was carried out, and finally the scene was projected on Monitor B. Each device was linked through the above-mentioned FASPULS to realize not only supplying power to each Gateway from a power source unit contained in the MASTER device but also communicating with each other through a single wire harness. Figure 20 shows a picture of the test system when carrying out the demonstration test using the SiPhON system.

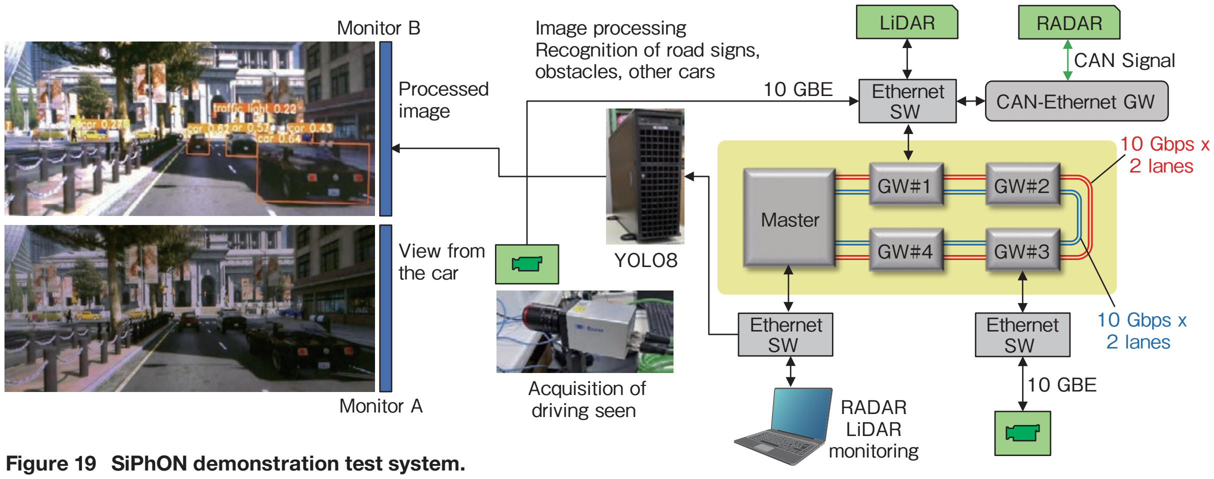


Figure 19 SiPhON demonstration test system.

Figure 20 Test system picture during transmission demonstration.

6. CONCLUSION

As the result of this research, we have demonstrated that high-speed communication would be achievable through multi-stage links of independent CW light sources and optical modulators. It is necessary to reinforce the number of linking stages of the Gateway devices and to reduce the loss of modulator devices for maintaining the loss budget (allowable transmission loss) in order to put the SiPhON system to practical use and to spread its use. Moreover, the evolution of heat control technology against heat generation and the advanced economical production technology are required as well. From now on, we are directing our development to aim at societal implementation around 2036 when no less than 50 Gbps bandwidth will be required for the in-vehicle optical communication after developing highly reliable optical modules which conform to severe weather conditions and complicated urban environment and improving the implementing bandwidth of all the components such as semiconductor packages, substrates and any others related to the implementation.

ACKNOWLEDGEMENTS

This research and development was achieved in “Research and development of infrastructure technology for large-capacity in-vehicle optical networks for highly automated driving” of contract research #21801 from FY 2020 to FY 2023, and in “ Research and development of high-performance and highly reliable in-vehicle optical network infrastructure technologies for fully autonomous driving” of contract research #23701 from FY 2024 sponsored by National Institute of Information and Communications Technology (NICT). We wish to express our deepest appreciation to Mr. Hiroyuki Tsuda and Mr. Ryogo Kubo of Keio University, Mr. Yoshiaki Nakano and Mr.Takuo Tanemura of the University of Tokyo, Mr. Yasushi Amamiya and Mr. Yongwi Kim of MegaChips Corporation, and Mr. Ryo Takahashi, Mr. Naokatsu Yamamoto and Mr. Atsushi Matsumoto of National Institute of Information and Communications, who kindly promote this research in collaboration with us.

REFERENCES

1) IEEE Standard for Ethernet Amendment 7: “Physical Layer Specifications and Management Parameters for Multi-Gigabit Glass Optical Fiber Automotive Ethernet”, IEEE Std 802.3cz™.
2) Hiroyuki Tsuda, Ryogo Kubo, et al.: “High Reliability and Large Capacity In-Vehicle Optical Network Applied with Multi-Function Photonic Integrated Circuits”, the Society Conference of the Institute of Electronics, Information and Communication Engineers, B-10-32 (2021). (in Japanese)
3) Onur Alparslan, et al.: “A Zone-Based Optical Architecture for Intra-Vehicle Backbone Networks”, the Photonic Network (PN) Research Group, IEICE Technical Report, vol. 121, no. 386, PN2021-79, 142-147 (2022). (in Japanese)
4) Shinichi Arakawa, Masayuki Murata, et. al.: “Reliability Evaluation of for Failures of Laser Diodes in In-Vehicle Optical Network, the SiPhON”, the Photonic Network (PN) Research Group, IEICE Technical Report, vol. 122, no. 398, PN2022-65, 125-129 (2023). (in Japanese)
5) Shinichi Arakawa, et. al.: “Research and Development of Large Capacity In-Vehicle Optical Network, the SiPhON”, the Communication System (CS) Research Group, IEICE Technical Report, vol. 123, no. 32, CS2023-5, 20-25 (2023). (in Japanese)
6) Shinichi Arakawa et al.: “Demonstration of a Highly Reliable Si-Photonics-Based In-Vehicle Optical Network (SiPhON) for Autonomous Driving”, ECOC’24 (2024).
7) Ryo Takahashi, Masayuki Iwase and Hiroyuki Tsuda: “The Latest Trend of In-Vehicle Optical Networks”, The journal of the Institute of Electronics, Information and Communication Engineers vol. 107, no. 2, 2024, 128-134 (2024). (in Japanese)
8) Takanori Toyama, Kouhei Ikemoto et al.: “Development of the Wiring System Technology to Realize its Weight-Reduction in Vehicles”, Furukawa Electric Review 53 (2022).