Review

Visible Optical Fiber Communication

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Abstract

This paper provides an overview of recent developments affecting in-vehicle optical networks. Visible light sources are now being used in this field, bringing advantages in both visibility and workability. In particular, current trends and subjects affecting the key devices used in these networks, such as visible light sources, optical fibers, optical circuits and transceiver modules, are explained. We consider that the use of a wavelength division multiplexing (WDM) technology is promising for realizing further advances in high-speed communications. We will briefly introduce the optical devices for WDM that have been developed in our research group.

Keywords Automotive network, Optical network, LED, Waveguide, WDM communication

1. Introduction

In the past decade, broadband-communications technology using optical fibers has spread quickly through Internet lines and cable TV lines to the home.

This is a result of the cheaper cost for optical fiber communication systems that realize the transmission speeds required by those services when compared with copper wire-based systems. Acute competition within the field of electronic communications is still continuing in these applications.

It is now believed that the amount of information that will need to be transmitted in the field of automobile technology will increase rapidly in the near future, not only in information systems, but also in control systems and safety systems,[1)] and an increase in network data rates is urgently required.

In several European vehicles, the provision of optical networks has already started in luxury grade models,[2)] and it is considered that a sharp turning point from metal networks to optical networks will arrive in the near future.

In this review, we introduce trends in transceiver technology for automobile optical LANs and give a brief overview of research activity at the Toyota Central R&D Labs.

2. Optical networks for automobiles

2. 1 History

The increased use of electronics in automobiles has seen the installation of multiple networks in modern cars, and the expansion of these systems has quickly accelerated. There are three principle networks that are used in cars, known as the information, control, and body systems. The information system deals mainly with entertainment devices such as in-car navigation and DVDs, while the control system deals the devices like cruise-control and other safety systems. The body system includes networks for switches or actuators. In recent years, increases in the network data rate for information and control systems are remarkable, and some European car makers have now adopted an optical fiber network since 1998.[3)] **Figure 1** shows the transition in data rates that have formed the specifications adopted for the network systems used in actual vehicles. It shows that the rate is steadily increasing by about ten-fold every five years. Thus, improvements in network speed will still continue, and advanced features and reduced costs for metal-wired systems are being energetically pursued, so it is considered that competition with optical fiber will continue for the time being. At present, for high speed applications of more than 10 Mbps, in-vehicle network standards are mainly being discussed in terms of using optical fiber, as shown in **Fig. 2**. Among these optical network standards, the system known as ByteFlight (data rate 10 Mbps)[4)] has been adopted for control systems, and the Digital Domestic Bus (D^2B)(5.6 Mbps) and the Media-oriented System Transport (MOST)(22.5 Mbps) standard[5)] for information systems have been adopted for actual in-vehicle networks. Though MOST2 (50 Mbps) is under discussion as a next-generation standard to follow the MOST standard,

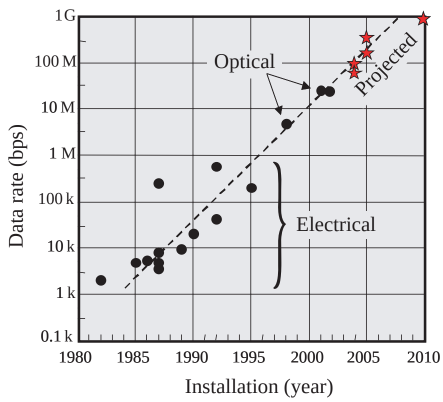


Fig. 1 Transition in data rates (actually installed and projected) for in-vehicle networks.

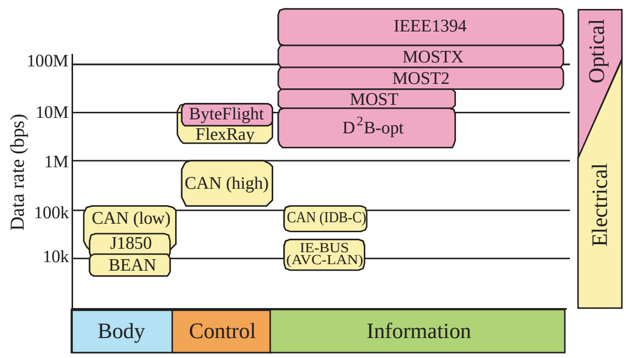


Fig. 2 Network standards for the automotive industry.[9)]

there are two working groups using optical or electrical protocols within the MOST consortium, and competition has also occurred here. IDB1394[6] has also been discussed for next generation in-vehicle information network systems since 2000. This standard features compatibility with IEEE1394 (125/250/500 Mbps), which is a wide-spread standard for digital household appliances. On the other hand, the standardization organization AMI-C (established in 2001)[7] which was founded by the automobile manufacturers, is also carrying out original initiatives. These three high-speed standards are expected to appear successively in the near future.

In the field of control systems, FlexRay[8], which has a maximum data rate of 10 Mbps, is being discussed as the global standard to replace CAN, and the development of a network that promotes X-by-wire technology is expected. If FlexRay is put into practical use, it is believed that the development of safety and comfort-based driving systems will be given a spur forward, especially in relation to on-board camera systems and semi-automatic cruising systems for accident prevention.

2. 2 Visible light sources and optical fiber for automotive networks

In public networks and premise-based local area networks (LAN), the demand for high-speed and long-distance transmission is high, and a combination of infrared laser diodes (LD) and silica optical fibers has mainly been used. On the other hand, since in-vehicle networks are only employed for relatively short distances at low speed (<50 Mbps), a combination of red LEDs and plastic optical fiber (POF) has been used.[10] The use of POF has been adopted for the following reasons;

- Enables low cost network systems (Physical layer),
- POF is low-loss in the red region of the spectrum,
- Since the diameter of POF is about 1mm, its coupling efficiency with LEDs (emitting area about 300 μm square) is high.

The commercialization of GaN emitting devices has recently started to occur, and blue and green LEDs are now being studied as potential light sources for optical communication systems. In fact, because LEDs of these colors are superior to conventional red LEDs in many respects, including a lower loss band in POF (see **Fig. 3**), lower deterioration of emitted power in high temperature environments and excellent in high-speed operation, the large-scale adoption of blue/green devices is expected in the near future (the details are described in this special issue).[11]

For high-speed serial communication at more than 1 Gbps, the combination of an LD and a graded refractive index-(GI)-type broadband optical fiber is required. However, the wavelength of VCSELs (Vertical Cavity Surface Emitting Laser)[10] that have been developed as low-cost LDs for data communication is more than 780 nm, and transmission over 10 m in conventional PMMA-based POF is impossible due to high absorption loss in the fiber. Although both GI-type silica fiber and GI-type fluororesin-based POF have been identified as having some potential for transmitting such wavelengths over 10 m at 1 Gbps, they have the disadvantage of leading to a steep increase in system costs.

In terms of installation demands, because optical fibers are typically assembled into the bundle that forms the electrical wiring harness (**Fig. 4**), a minimum-bending radius of about 15 mm is required in order to minimize the influence of transmission loss. In each of the standards under consideration, in order to suppress the deterioration of transmission power due to bends with a small radius, it has been determined that a large refractive-index difference between the core and the cladding is required. In POF with a diameter of 1 mm, a numerical aperture

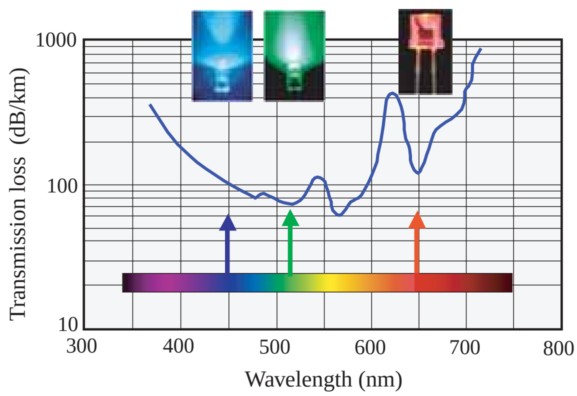


Fig. 3 Transmission loss of PMMA-based POF and the emitting wavelength of several of the LEDs discussed in this special issue.

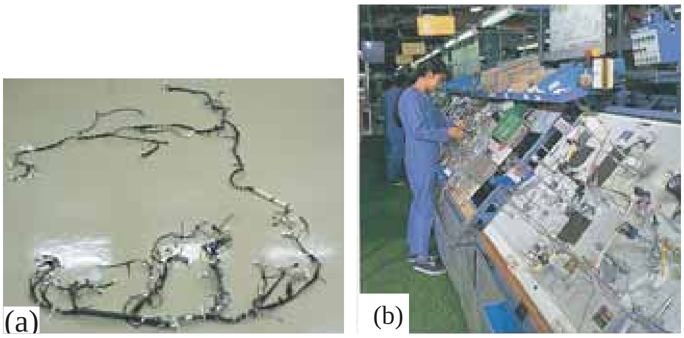
of between 0.5-0.65 is considered as the minimum requirement.

2. 3 Optical circuits and transceivers

Optical communication technology is spreading through many consumer-oriented electronic products, and cost reductions in these systems are in strong demanded. Many of these devices are quite compact, and it is often difficult to find the space to connect them using large-sized optical connectors. Moreover, cables that are easy to install (high flexibility of bending) are required. Due to these demands, systems that offer bi-directional communication over a single optical fiber have been proposed for many of the standards that operate in these different fields. In these bi-directional systems, since the amount of optical fiber required and the space needed for the connectors can be reduced by half, large cost savings can be expected.[13)] Moreover, because this system easily reduces installation costs and device costs, its use in automobile applications has been studied widely. Generally speaking, full-duplex single-fiber bi-directional communication systems suffer from troublesome optical crosstalk between the transmitted signal and the received signal, which can become a serious problem. Fortunately, since the communication distance is usually short in consumer-oriented electronic products, the signal-to-noise ratio becomes relatively large and this problem can be solved relatively easily.

In order to realize optical transceivers for single fiber bi-directional communications, an optical circuit to separate and to combine the transmitted light and the received light is needed. Various types of optical circuits have already been proposed in the field of automotive engineering. **Figure 5**(a) shows an example designed for half-duplex operation (alternate communication between both transceivers) that was introduced in the BMW 7-Series. In this optical system, a red LED chip is mounted on a large-area photo diode (PD) chip using "chip-on-chip technology".[4)] Since the LED does not emit light while the PD is receiving a signal, electrical and optical crosstalk theoretically do not arise. The device can operate with a maximum transmission rate of 10 Mbps in the ByteFlight[14)] system, and higher speed devices have also been investigated.[4)]

An optical module for full-duplex communication that uses the principle of dividing light beams is also under investigation.[15)] Because the outgoing beam from a VCSEL has strong directivity, the outgoing beam from a VCSEL can even couple efficiently into an optical fiber after reflection at a micro-mirror, as shown in Fig. 5(b). Conversely, about half of the weak-directivity outgoing beam from the fiber can be coupled directly into a large PD; the remainder is lost due to reflections at the mirror. This device seems to be a simple structure, but it requires the implementation of precise mounting technology and has issues in terms of both electrical- and optical crosstalk due to proximity arrangement. Especially, the optical crosstalk is strongly



(a) (b)

Fig. 4 Photographs of (a) a wiring harness[12)] and (b) an assembly plant.[9)]

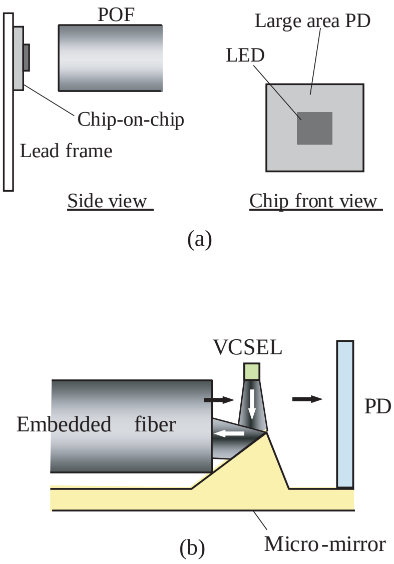


Fig. 5 Examples of devices constructed using bi-directional optical modules for automotive applications.[4, 15)]

influenced by the device surface arranged in the neighborhood and directivity of the light source. The optimal arrangement which realizes large tolerance and a small crosstalk is a subject for future studies.

2. 4 Multiplexing communications and future developments

Drastic cost reductions cannot be expected by simply replacing metal cables with optical cables. In order to promote the conversion to optical cable, it needs to be accompanied by additional merits, such as a drastic reduction in the amount of wiring required and a saving in weight by using optical fiber technology. For this reason, time-division multiplex (TDM) communication and wavelength multiple (WDM) communication systems have been proposed.

In TDM, a high-speed optoelectronic device, a clock-conversion device and a communication control device are needed, which counterbalances the effects of reducing the amount of wiring. For example, we will now consider multiplexing the three different digital signals shown in **Fig. 6**(a). In this case, each bit of data must merge into a pre-determined data stream at a data rate that is more than three times higher, after conversion of the data into the same format. Also, the use of a buffer and associated hardware are needed for these clock conversion devices, and we are anxious about raising the cost of the electronic components that are required. In addition, the reliability of using TDM to combine the signals can be variable, and there are many issues that still need to be solved, such as fixing system specifications and security levels, not to mention the complexity involved in system modification.

On the other hand, WDM communication is a method of simultaneously transmitting light-signals using different assigned wavelengths through a single optical fiber, as shown in Fig. 6(b). Since the nature of light prevents the mixing of different wavelengths, if wavelength-separation can be achieved using a prism or a color filter at the end of the fiber, then the light can be easily separated into signals of different wavelengths. In a WDM system, multiple signals simply share the same optical fiber, and there is no necessity to match the data format between signals (data rate, coding/encoding, analogue/digital, etc.). Therefore, a protocol for multiplex communication (a different protocol is assigned and multiplexed for different wavelengths) by WDM becomes possible without the need for complex and costly data-format-matching (arbitration free). However, this system requires multiple light sources of different wavelengths and costly multiplexers and de-multiplexers (mux/demux) for those wavelengths.

Although both of these transmission systems have already been put into practical use in public networks, their application to automotive networks can be difficult in terms of both durability and cost.

3. Brief description of our activities

As mentioned above, in the field of in-vehicle networks, several network systems involving differing specifications have been rapidly expanded. In order to realize lower costs and to reduce the amount of wiring required in high-speed networks, we believe that sharing of the communication line

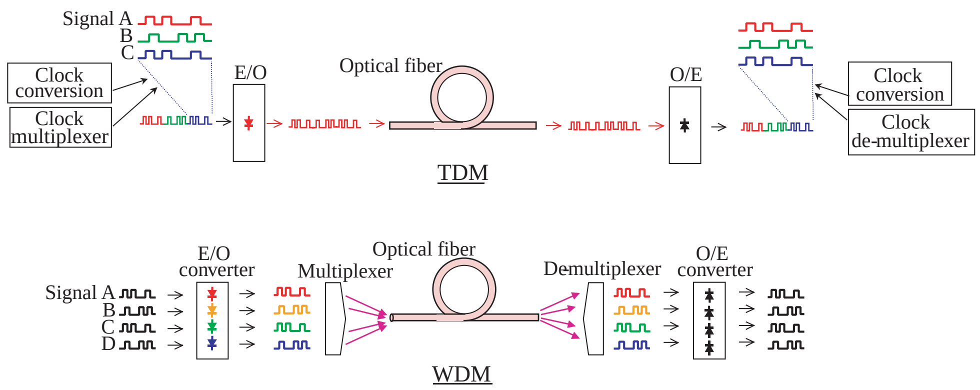


Fig. 6 A comparison of transmission systems using TDM and WDM.

by several signals that do not interfere with each other is a promising approach for unifying the various communication standards (**Fig. 7**). We believe that a system based on WDM is the most suitable solution, and we consider that this system is also promising in terms of future expandability (number of wavelengths, data rate).

In general, although LDs are used in high-speed optical communication systems, the use of LEDs is preferable in automobile applications in respect of stability in high-temperature environments and low system costs. However, since high-speed operation and the range of available wavelengths are limited, the practical implementation of WDM using LEDs has not occurred as yet. In our research group, studies aimed at overcoming the above-mentioned technical subjects that affect WDM systems are well advanced.

In this special edition, we introduce as an example of a WDM system[16] that uses visible light sources in a single fiber bi-directional communications module, focusing on the individual device technologies that are involved. We will introduce our results in subsequent papers, including topics such as; high speed LEDs that emit in a newly-available visible wavelength region, low-cost optical waveguide technology for mux/demux optical circuit fabrication, and a bi-directional optical transceiver module that consists of LEDs and a mux/demux optical circuit.

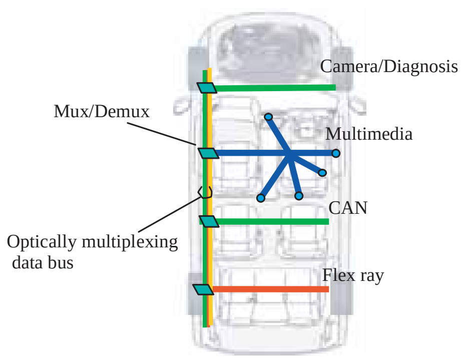


Fig. 7 Basic concept of automotive multi-protocol communication using WDM.

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