



**Asia-Pacific Telecommunity**

**APT Report on  
Characteristics and Requirements of  
Optical and Electric Components for  
Millimeter-wave Radio on Fiber systems**

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## 1. Introduction

Radio on Fiber (RoF) system can provide low-cost and high-performance radio-wave distribution by using remote access units (RAUs) where lightwave modulated by radio-wave is converted to radio-wave by a high-speed photodetector (PD) [1]. In microwave bands, RoF systems are successfully used for mobile services to provide signals to the mobile terminals located at such shadowing areas as underground, tunnel and inside buildings. As well known, millimeter-wave can carry high-speed data streams [2]. However, very high-frequency signals should be synthesized at a number of base stations (BSs) to cover a large area. RoF systems can provide low loss and cost effective millimeter-wave signal distribution and collection of millimeter-wave signals at many small cells. Thus, millimeter-wave broadband wireless systems with RoF would be promising a new generation wireless access or local area networks that would bring the cost-effective broadband infrastructure for access systems for APT countries.

This Report provides information on characteristics and requirements of optical and electrical components for millimeter-wave RoF systems. Components of high-speed electric-to-optical (E/O) and optical-to-electric (O/E) conversion devices designed for optical digital systems would be useful for millimeter-wave RoF systems. Because requirements of components for RoF systems are quite different from those for digital systems not only the system characterization techniques but also E/O and O/E components specialized for RoF are very important for designing RoF systems. Annex 1 summarizes information on characterization of E/O and O/E conversion devices for information..

## 2. Scope

This report provides information on optical and electric components for RoF systems in millimeter-wave bands and guidance for each administration to design cost-effective and broadband infrastructure using millimeter-wave RoF systems. The outline and applications of the RoF systems are also described to define requirements of the components.

## 3. Abbreviations and acronyms

10GbE	10 Gigabit Ethernet
AWG	Arrayed waveguide
BER	Bit-error-rate
BS	base station

CA	Cassegrain antenna
CU	Central unit
EA	Electro-absorption
EO	Electro-optic
E/O	Electric-to-optical
GOA	Gaussian optic lens antenna
LN	Lithium niobate
MZM	Mach-Zehnder modulator
OC-192	Optical carrier 192 A SONET rate of 9953.28 Mbit/s (payload: 9621.504 Mbit/s; overhead: 331.776 Mbit/s) over optic fiber lines. SONET stands for Synchronous Optical NETWORK.
O/E	Optical-to-electric
PD	Photodetector
RAU	Remote access unit
RoF	Radio on fiber
SFN	Single frequency network
UTC-PD	Uni-travelling-carrier photodetector
VNA	Vector network analyzer

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## 5. Outline of RoF systems

Figure 1 shows a schematic of the RoF system consisting of components for E/O or O/E conversion and of an optical fiber for transmission. The loss in the fiber is very small. For example, the transmission loss of a standard single mode fiber is 0.2dB/km for lightwave with wavelength of 1550nm. In conventional RF signal distribution systems, transmission loss in metallic cables or waveguides would be particularly large for high-frequency signals. The loss largely depends on the signal frequency, while that of RoF systems is almost constant. Thus, the transmission loss would be negligible in RoF systems for short distance transmission (shorter than 10km). The total gain or loss of the systems is largely depends on the efficiency of E/O and O/E conversion. The intensity and quality of millimeter wave radiated from antennas at BSs directly depend on the performance of the components in the systems, while the millimeter wave depends only on the performance of BSs in millimeter wave systems with digital transmission based backbones.

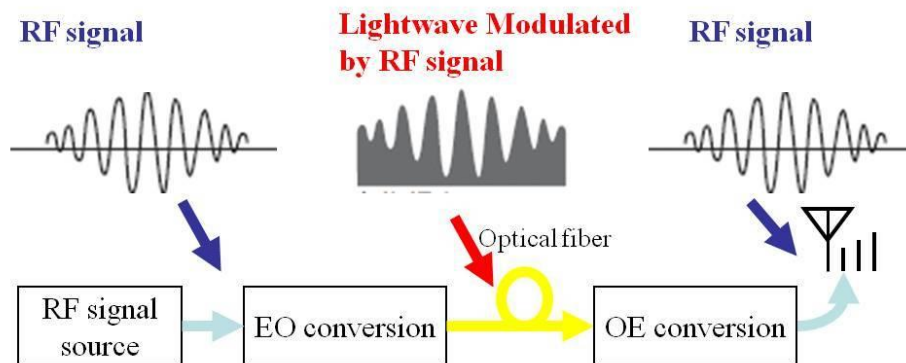


Figure 1 Basic concept of RoF system.

## 6. Key optical devices for millimeter-wave RoF systems

E/O and O/E conversion play important roles also in digital data transmission systems. By using broadband electric and optical components, very high-speed optical links whose modulation speed is larger than 50 Gbaud have been demonstrated, recently. The components and sub systems designed for high-speed digital modulation and demodulation can be used for E/O and O/E conversion of millimeter-wave signals in RoF systems. Total performances of RoF systems rely on other components such as amplifiers, as well as on E/O or O/E devices of which overviews are in the following two sub-sections. As an example, impact of optical amplifier transient on link performance is briefly described in section 6.3.

### 6.1 E/O conversion devices

Direct modulation of a laser diode provides a simple E/O conversion setup. However, due to limitation of intrinsic response of the laser, it is difficult to modulate light by millimeter-wave. In addition, direct modulation generates undesired parasitic phase modulation which would degrade intensity modulated signal waveform by dispersion effect in the optical fiber. External modulation can provide high-speed E/O conversion. There are two types of external modulators: electro-optic effect (EO) modulator and electro-absorption effect (EA) modulator. EO modulators using lithium niobate (LN) which can provide high-speed and precise lightwave control would be useful for characterization of components for RoF systems, as well as for RoF systems themselves [3]. EO effect shifts the optical phase, so that optical amplitude or intensity can be controlled by using optical interferometer structures. A most popular one is a Mach-Zehnder modulator (MZM) consisting of a Mach-Zehnder interferometer which can provide wideband operation, as shown in figure 2 [4].

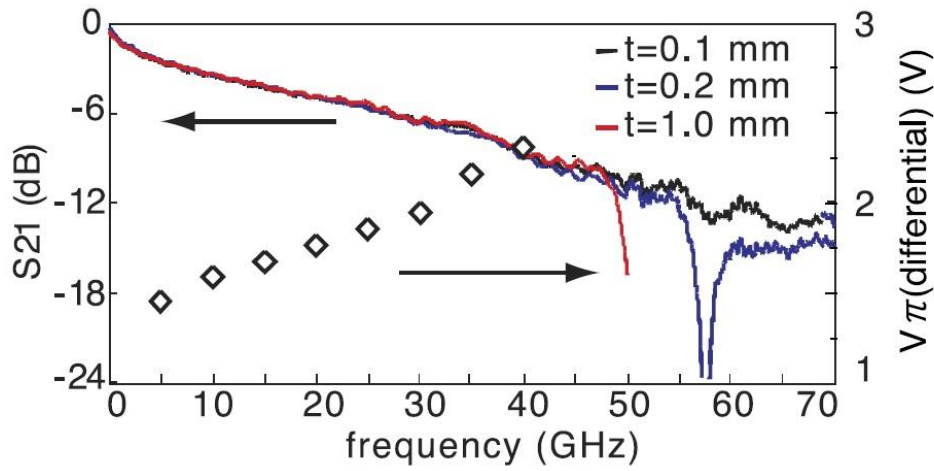


Figure 2 Frequency responses of high-speed MZMs of various device thicknesses ( $t$ ). Solid lines show  $S_{21}$  of electrodes in MZMs. Diamonds are half-wave voltages ( $V\pi$ ) for push-pull operation with dual electrode MZMs [4].

### 6.2 O/E conversion devices

For OE conversion, high-speed PDs have been developed to achieve wideband response (see figure 3). Uni-travelling carrier PDs (UTC-PDs) can provide high-speed and high-power operation, so that they would be useful for millimeter wave RoF systems [5]. Required bandwidth for the components would be 0.7-0.8xM-GHz for M-Gbaud binary digital modulation format transmission systems, so that technologies for 100-Gbaud can be applied for millimeter-wave RoF systems where the frequency would be 30-70GHz. However, the efficiency of the E/O and O/E conversion is directly connected to the intensity of millimeter-wave generated by the O/E conversion, while small deformation of the efficiency in frequency domain does not affect on the performance of the digital transmission. Components for digital transmission are designed for broadband operation from a few kHz to millimeter-wave frequency. On the other hand, RoF generates signals in a particular frequency region, so that O/E or E/O devices using resonance can be used where the efficiency is enhanced at a desired frequency. Thus, precise estimation of the O/E and E/O conversion efficiency in particular frequency ranges would be very important to assemble RoF systems (see annex 1).

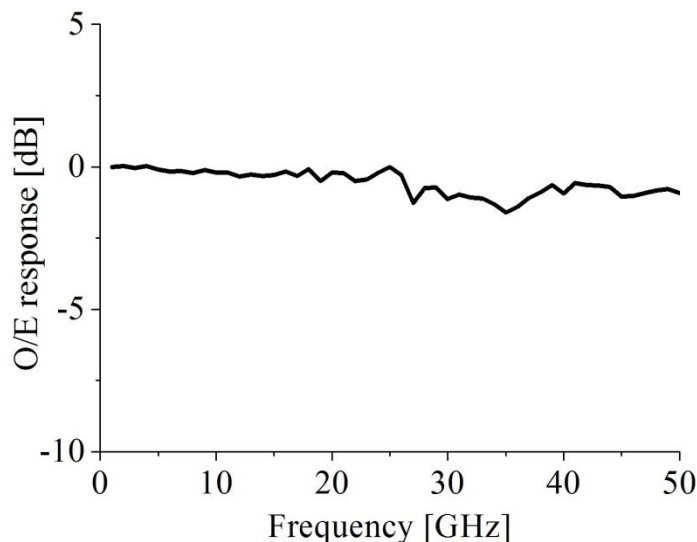


Figure 3 PD frequency response measured by optical two-tone stimulus method [6].

### **6.3 Impact of optical amplifier transient on link performances**

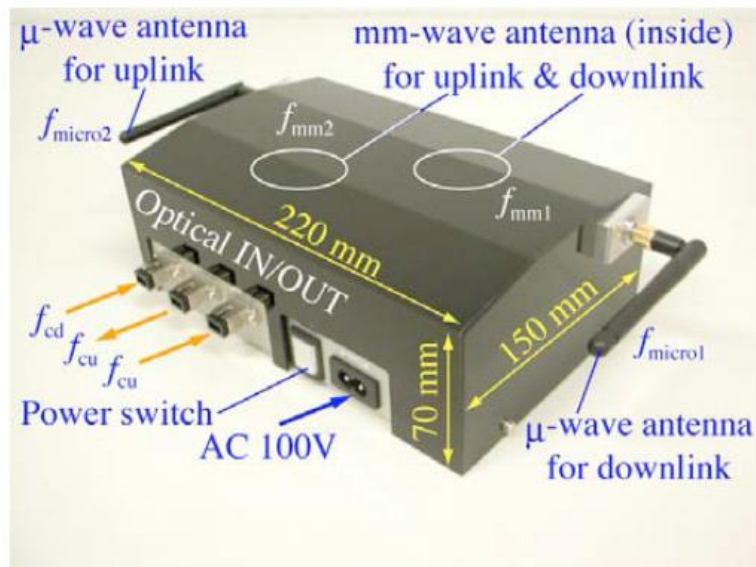
Large scale RoF systems would have optical amplifiers to compensate optical loss at power splitters, optical filters, etc. Dynamic gain transition in the amplifiers would have negative impact on the performance of RoF. When the amplifiers are shared with digital systems, bursty digital signals cause optical surge or distortion of RoF signal envelop. The transience is driven by cross gain saturation. Thus, bursty digital channels will affect the effective gain of channels assigned for RoF, and cause fluctuation of millimeter wave power radiated from antennas. Transient suppressed optical amplifiers using large core are proposed to control radiation power precisely [7].

## **7. Possible applications of millimeter-wave RoF systems**

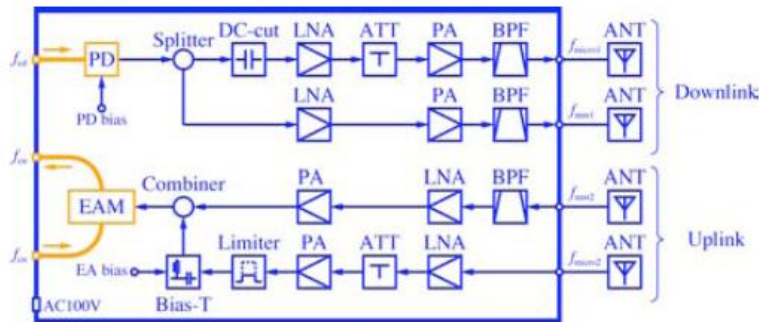
This section provides examples of millimeter-wave RoF systems. The microwave RoF systems which were implemented for mobile and broadcasting services are attached in Annex 2.

### **7.1 Application to mobile service: Microwave/Millimeter-Wave Dual-Band RoF System**

A dual-band RoF system, which simultaneously transmits millimeter-wave signals for high-speed data as well as conventional microwave-band signals, has been proposed [8]. Figure 4 shows a prototype BS for the dual band system. A high-speed PD with the 3-dB bandwidth of 60 GHz can generate millimeter-wave and microwave signals simultaneously from a RoF signal. An EA modulator converts millimeter-wave and microwave signals into a lightwave signal. The size was 220 mm (width) x 150 mm (height) x 70 mm (depth) with the exception of projecting parts of microwave-band antennas. Frequency bands of the millimeter-wave downlink and uplink were designed to be in 59 to 60 GHz and 61 to 62 GHz, respectively. The microwave link band was designed to be in 2412 to 2484 MHz. The transmission distance from a central unit (CU) to the BS was 2-km. The bitrate of the millimeter-wave link was 156-Mb/s.



(a)



(b)

Figure 4 Dual-band BS prototype: (a) photograph and (b) configuration [8] .

## 7.2 Application to fixed service: 120-GHz band high-speed wireless system based on millimeter-wave RoF technology

Recently, 10Gb/s 120GHz-band wireless transmission was demonstrated by using millimeter-wave RoF technology [9]. As shown in figure 5, signal transmitter consists of optical millimeter-wave signal generator, optical modulator and high-speed PD. Lightwave signal modulated by a millimeter wave signal of 125GHz is generated at the optical millimeter-wave signal generator, by using an MZM for sideband generation and an arrayed waveguide (AWG) for filtering. Another optical intensity modulator modulates the lightwave signal with 10-Gb/s data. Finally, the lightwave which carries a millimeter-wave signal intensity modulated by 10-Gb/s data is applied to the high-speed PD through an optical fiber. A UTC-PD was used to achieve high-speed response and high-power output. The transmission was demonstrated with 9.953 Gb/s (OC-192) and 10.3125 Gb/s (10GbE). Figure 6 shows the experimental 120GHz radio station which has a Cassegrain antenna (CA). A Gaussian optic lens antenna (GOA) was also tested. Table 1 shows the specification of the radio station. BER of  $10^{-12}$  was achieved with a received power of -32.5dBm for 9.953 Gb/s, and -30.2dBm for 10.3125 Gb/s. The wireless transmission distance was 200m for 9.953 Gb/s and 300m for 10.3125 Gb/s.

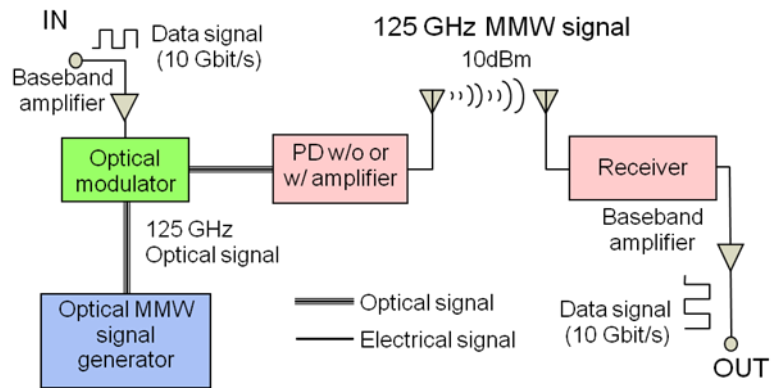


Figure 5 Schematic of 10-Gb/s wireless link by RoF technology [9].

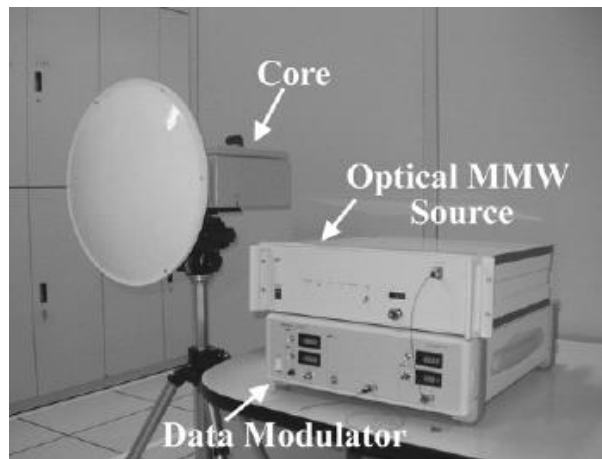


Figure 6 Experimental 120GHz radio station [9].

Table 1 Specification of the experimental radio station [9].

Center Frequency	125.000 GHz
Occupied Bandwidth	116.5-133.5 GHz
Output Power	10 mW
Antenna	Cassegrain Antenna (CA) Gaussian Optic Lens Antenna (GOA)
Antenna Gain	48.7 dBi (CA), 52 dBi (GOA)
Antenna Diameter	450 mm (CA), 300 mm (GOA)

## 8. Summary

This report considers characteristics and requirements of optical and electric components for millimeter-wave RoF systems. In millimeter-wave region, signal transmission by metal cables is not feasible because the loss in the cables would be significantly large. On the other hand, the loss in optical fibers does not depend on the signal frequency. Thus, we can achieve long distance transmission of millimeter-wave by using RoF. Lasers, optical modulators and PDs play important role in RoF systems. Optical components designed for high-speed digital optical communication systems could be used for analog systems including RoF systems. However, the requirements would be different from digital systems, so that characterization and measurement of components would be very important to assemble RoF systems.

### Annex 1: Characterization of E/O and O/E conversion devices for RoF

As described in the previous sections, precise characterization of optical devices plays important roles in millimeter-wave RoF systems. Vector network analyzers (VNAs) are often used to estimate frequency response of high-speed electric components, such as couplers, transmission lines, amplifiers, etc., as shown in figure 7.

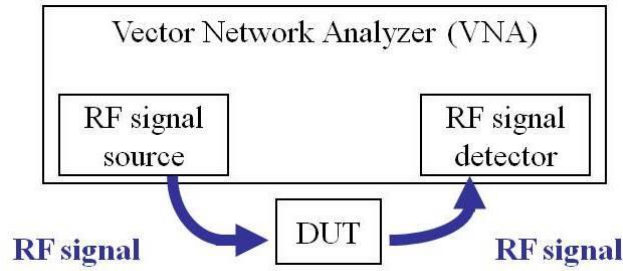


Figure 7 Frequency response measurement for electric components using a VNA.

A VNA with optical interfaces consisting of E/O and O/E converters can be used for estimation of O/E or E/O conversion devices, where optical devices in the optical interfaces should be precisely calibrated. A calibrated O/E converter is needed to measure the efficiency of E/O conversion, as shown in figure 8. Similarly, a calibrated E/O converter should be used for estimation of O/E devices (see figure 9).

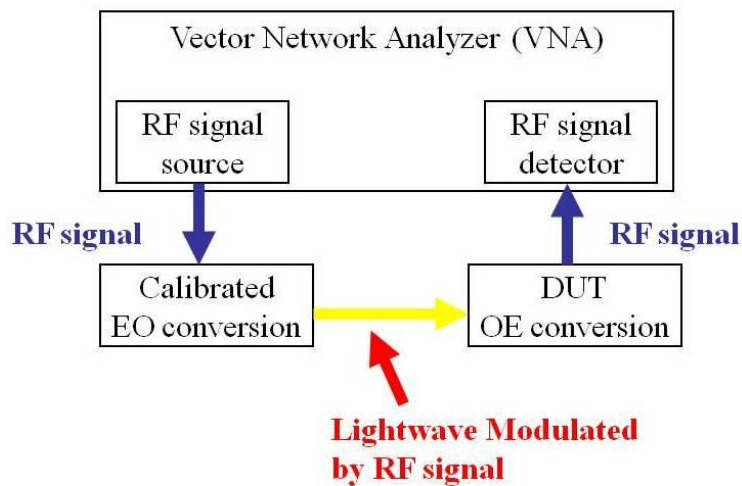


Figure 8 Frequency response measurement setup for O/E conversion.

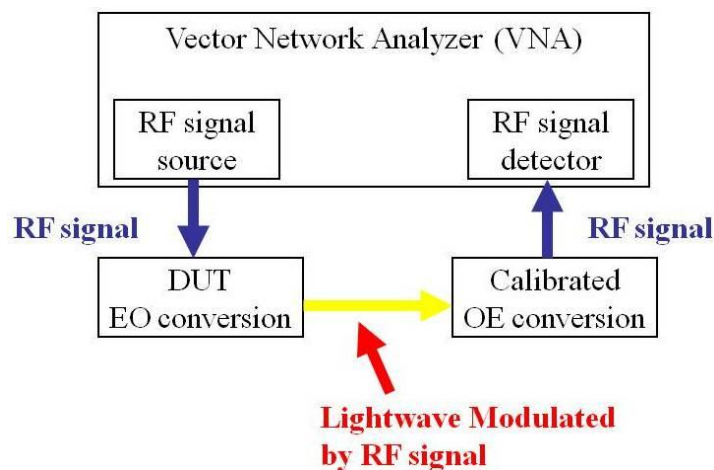


Figure 9 Frequency response measurement setup for E/O conversion.

On the other hand, recently, measurement techniques for characteristics of MZMs based on optical spectrum analysis have been proposed, where relative optical intensities of sideband components are

measured by an optical spectrum analyzer without using a high-speed PD [10]. These techniques are specialized for MZMs, but MZMs can provide high-speed and precise lightwave control. Thus, a reference signal for measurement of performance of various types of E/O and O/E conversion devices can be generated by an MZM. A pure two-tone optical signal can be generated by using high extinction ratio optical modulation [3]. The two-tone optical signal can be used for a reference signal to calibrate O/E conversion devices. The following steps provide calibration of a PD and an optical modulator.

- 1) To measure an MZM by using optical spectrum analysis.
- 2) To generate a two-tone optical signal by using the calibrated MZM.
- 3) To measure frequency response of a PD by feeding the two-tone signal.
- 4) Any optical modulators can be calibrated by using the calibrated PD.

Finally, a pair of optical interfaces with E/O and O/E conversion can be calibrated. Thus, a measurement setup for any E/O or O/E conversion devices can be constructed, where the VNA is connected to the calibrated interfaces. In this procedure, the measurement technique for MZMs based on optical spectrum analysis, and the frequency response measurement using an optical two-tone signal for high-speed PDs play important role for low-cost and precise measurement of performance of optical components designed for RoF systems.

## **Annex 2: Applications of microwave RoF to terrestrial services**

This annex provides examples of microwave RoF systems for terrestrial services. A remote antenna system with RoF technologies has been developed for relaying radio waves in single frequency networks (SFNs), as shown in figure 10 [11]. This system has been developed for digital terrestrial TV broadcast radio waves. For SFNs, the receiving antenna should be separated from the antenna which transmits the radio wave received at the received antenna. A receiving unit (RU) has an antenna for receiving the radio wave from a parent station, and an optical modulator for generation of a RoF signal. A transmission unit (TU) transmits an unmodulated lightwave for modulation at the RU, and a high-power lightwave as a power source of the RU. The RoF signal transmitted from the RU is converted into an electric signal by O/E conversion at the TU. The distance between the RU and TU can be larger than 1km. In addition, lightning damage can be suppressed because the RU is electrically isolated from the TU. Figure 11 shows a compact RoF analog link system which can transmit signals from 60MHz to 3GHz, where the RF output power is equalized to be 0 dBm. The system consists of an E/O and O/E modules. The size of modules is 110 (135 include RF Connector) (W) × 46.5 (D) × 27(H) mm [12]. Optical and RF connectors, amplifiers and other components are installed in the small modules. Each module has an N-connector, so that it can be easily applicable to extension of RF signal transmission in conventional systems. Thus, it would be useful for filling gaps of broadcasting or mobile communication services in skyscrapers, underground shopping centers, subways, etc. Figure 12 shows a schematic of a gap filling system for mobile services in tunnels, where the system can be shared by plural service operators [13]. In subways in Tokyo and Osaka, Japan, 3G mobile services using this system will be started by March, 2012.

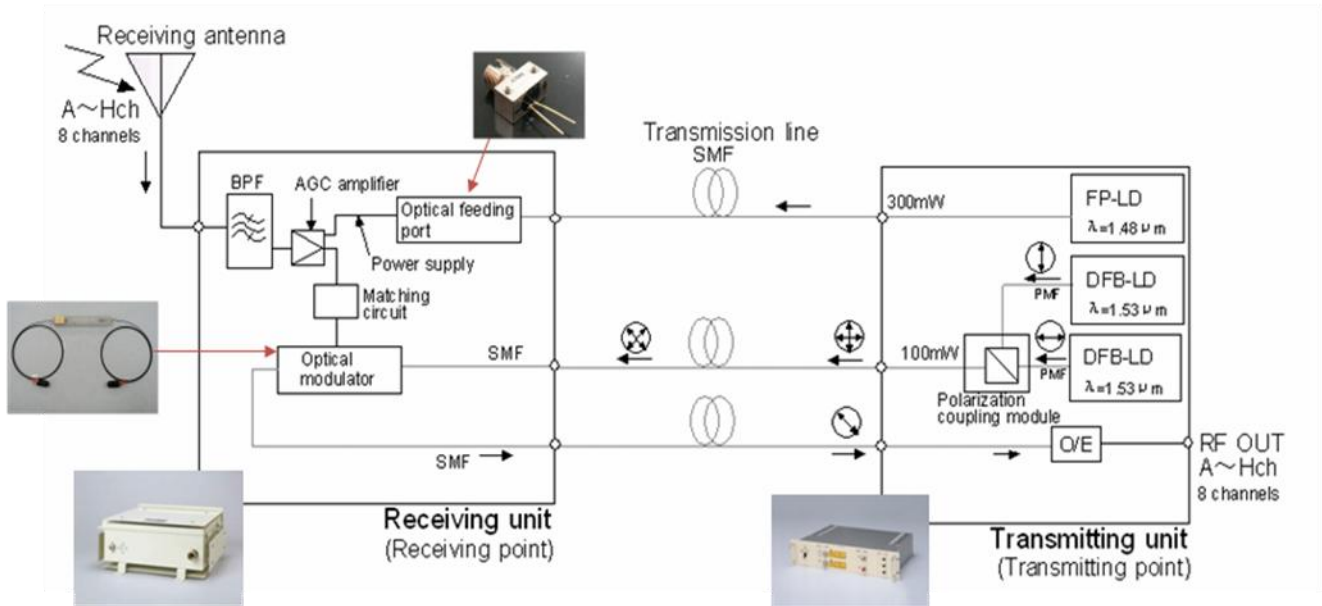


Figure 10 Remote antenna system for relay of digital terrestrial TV radio wave [11].



Figure 11 Compact RoF link system [12].

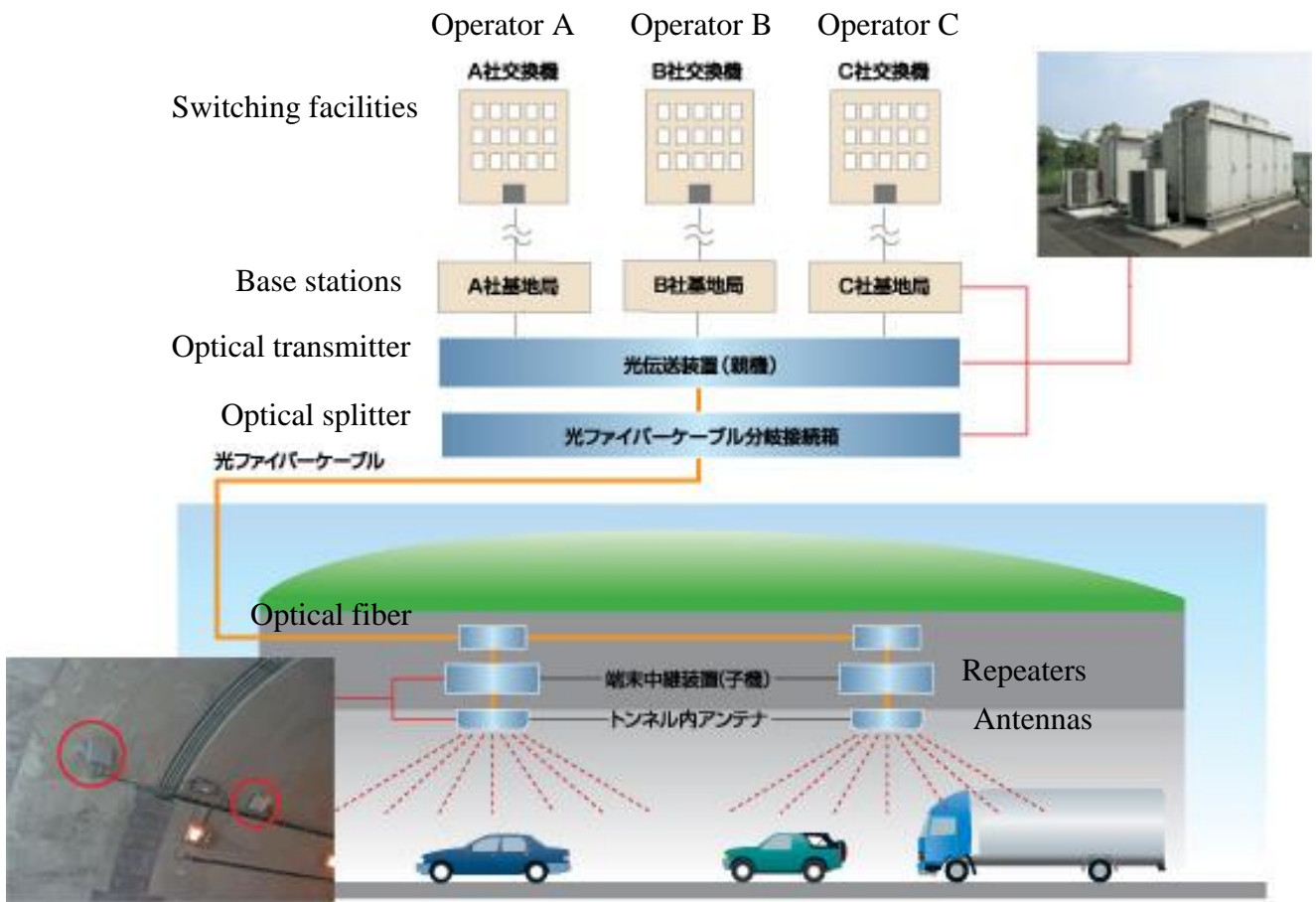


Figure 12 RoF system for filling gaps in tunnels [13].