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# Hybrid CATV/16-QAM-Digital CATV/16-QAM-OFDM in-building network over passive optical network and gradient index-plastic optical fiber/visible light communication transport

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**Abstract.** We propose and experimentally demonstrate a hybrid CATV/16-QAM-Digital CATV/16-QAM-OFDM in-building network over a 40-km single-mode fiber and graded index-plastic optical fiber/10-m visible light communication. The application of external injection technology with the addition of an optoelectronic feedback that raises the resonance frequency of the laser diode results in increased system transmission capability. Good performances of carrier-to-noise ratio, composite second-order, and composite triple-beat are obtained for the CATV signal. A low bit-error-rate value is achieved for the 16-QAM-Digital CATV/16-QAM-OFDM signal.
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Keywords: graded index-plastic optical fiber; passive optical network; injection and feedback; visible light communication.

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## 1 Introduction

Fiber-optic communication has become an important fundamental facility in the communication development of every country because it provides effective broadband integration communication service. To satisfy the increasing demand for broadband, the fiber-optic network has to be constantly improved.[1] With the development of receiving FTTx technology for an optical fiber, which is characterized by wide bandwidth, zero electromagnetic radiation, and low energy loss, such a fiber has become the most critical transportation medium in the wired communication field.[2–4] In addition, because wireless communication provides a way for people to retrieve messages and updates anytime and anywhere, it has become vital for daily life. However, meeting the rapid development of message technology generates an increased demand for high speed and wide bandwidth of indoor wired/wireless broadband access networks [e.g., plastic fiber-optic transmission system or visible light communication (VLC)]. A network structure built with a single-mode fiber (SMF) is well known to be capable of providing users high-quality transmission service. Such an advantage is more remarkable when it is utilized in long-distance and huge data transmissions. However, SMF may not be the best choice in a last mile indoor wired broadband access due to its installation cost and low convenience. To overcome such issues, a new development is required for the new indoor wired broadband access scenario. Achievements in research on gradient index-plastic optical fibers (GI-POF) and VLC have been widely proposed;[5–10] specifically, the optimum path to the last mile's solution. GI-POF not only has the same characteristics of SMF, as mentioned above, but also has the advantages of a large core diameter, excellent bending radius, and easy cutting and coupling for users. In addition, VLC has several strong points compared with traditional microwave radio communication in the field of indoor wireless broadband access. Among these strong points, it provides a free, license-free electromagnetic spectrum communication channel and no electromagnetic interference. Thus, it can be utilized in specific zones where radio frequency (RF) communication is prohibited (e.g., hospitals, oil refinery, and so on) to compensate for the inconvenience of RF communication. GI-POF and VLC may be used in the integration of a fiber backbone and an indoor broadband access network. The feasibility of SMF integrating with GI-POF to transmit a CATV/OFDM signal has been verified.[6] Transmission possibility through the integration of SMF and photonic crystal fiber through a mixed CATV/16-QAM-Digital CATV/16-QAM-OFDM signal that introduces light injection/optoelectronic feedback has also been verified.[11] The possibility of transmitting 40-km SMF and 30-cm VLC by integrating a passive optical network (PON) and a VLC structure through the use of LED to transmit a 500 Mbps signal for VLC has also been proposed.[7] However, neither integrating the mixed CATV/16-QAM-Digital CATV/16-QAM-OFDM with a PON of 13 wavelengths nor the GI-POF/VLC indoor broadband transmission has been proposed by any research team. Compared with the research proposed regarding mixed the optical fiber transmission system and VLC, the mixed CATV/16-QAM-Digital CATV/16-QAM-OFDM integrated with a PON of 13 wavelengths and the GI-POF/ VLC indoor broadband transmission has relatively bigger challenges to overcome. In this study, the system's transmission capability is increased through the application of an external injection technology with the addition of an optoelectronic feedback that raises the resonance frequency of the laser diode (LD). As far as we know, this study is the first to use external injection and optoelectronic feedback technology to integrate

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both plastic fiber and visible laser communication in a fiber transmission system. We expect a successful direct modulation of the CATV/Digital CATV/16-QAM-OFDM multifrequency signal and to receive good carrier-to-noise ratio (CNR), composite second-order (CSO), and composite triple-beat (CTB) status in CATV portion. A fairly low error rate and a beautiful horoscope chart in the 16-QAM-OFDM portion after transmission via 40 km of SMF, 10 m free space, and 30 m plastic fiber are also expected. The system offers complete broadband service for cable TV, telecom, and the Internet. It not only provides an integration of optical fiber backbone and indoor access, but also reveals its convenient last-mile application for final users, making it very appealing for advanced fiber-to-the-home (FTTH) application.

## 2 Experimental Setup

The experimental setup of our proposed hybrid CATV/16-QAM-Digital CATV/16-QAM-OFDM in-building network over a combination of 40-km SMF and 30-m GI-POF/10-m VLC transport is shown in Fig. 1. A total of 77 carriers (CH 2 to 40; 25 dBmV/CH and CH 41 to 78; 15 dBmV/CH) generated from a multiple-signal generator (Matrix SX-16) are employed to provide the CATV and 16-QAM-Digital CATV signals. The 16-QAM-OFDM data signal (5 Gbps/1.175 GHz; 0 dBmV/carrier) is generated offline via MATLAB and uploaded into an arbitrary waveform generator. To avoid intercarrier interference, the peak to average power ratio of the OFDM signal is limited to 8 dB. Such a 16-QAM-OFDM signal is represented by a 512 FFT size (including 128 data subcarriers, 64 cyclic prefixes, and 16 training symbols), 5G samples per second, and 1.175-GHz intermediate frequency. The CATV (CH 2 to 40), 16-QAM-Digital CATV (CH 41 to 78) signals, and the 16-QAM-OFDM data signal are combined by using a $2 \times 1$ RF combiner with a 2-GHz bandwidth. The distributed feedback LD (DFB LD1) with a central wavelength of 1312.46 nm ($\lambda_1$) is directly modulated by CATV (CH 2 to 40), 16-QAM-Digital CATV (CH 41 to 78), and 16-QAM-OFDM (5 Gbps/1.175 GHz) signals. The optical output of DFB LD1 was injected into the DFB LD2 via an optical circulator (OC) with an injection power level of 4.8 dBm. The OC placed between the DFB LD1 and DFB LD2 prevents the return of laser light, ensuring that the injection light is completely injected into the DFB LD2. The output of DFB LD1 is coupled with port 1 of the OC, and the injection-locked DFB LD2 is coupled with port 2 of the OC. Port 3 of the OC was separated by a $1 \times 2$ optical splitter. One part of the laser output is used for feedback through an optoelectronic feedback loop, and the other part is used for optical signal transmission. In the optoelectronic feedback loop, the fiber span between the OC and broadband photodetector (PD) is a fiber patch cord. The broadband PD converts laser light into a baseband, and RF combines signals to directly modulate DFB LD2. Over a 40-km fiber link, the optical signal is separated off by a $1 \times 2$ optical splitter. One of the optical signals passes through a 30-m GI-POF that has a core diameter of $50 \pm 5$ $\mu$m and a total power loss of 6 dB. The optical signal is then detected by a photodiode with a 3-dB BW of 2.5 GHz, split by a $1 \times 2$ RF splitter, filtered by two separate RF band-pass filters (BPFs) (50 to 550 MHz and 550 MHz to 2 GHz) to remove the spurious, amplified by two separate amplifiers [push-pull amplifier and low-noise amplifier (LNA)], and finally applied to a CATV analyzer and an OFDM analyzer. The push-pull amplifier has a 3-dB BW of 550 MHz, a signal gain of 22 dB, and a low noise figure (NF) of about 6 dB. Also, the LNA has a 3-dB BW of 2 GHz, a small signal gain of 24 dB, and a low NF of approximately 3.8 dB. All the CATV RF parameters (CNR, CSO, and CTB) are measured by a CATV analyzer, and the 16-QAM-OFDM signal is analyzed by an OFDM analyzer for bit error rate

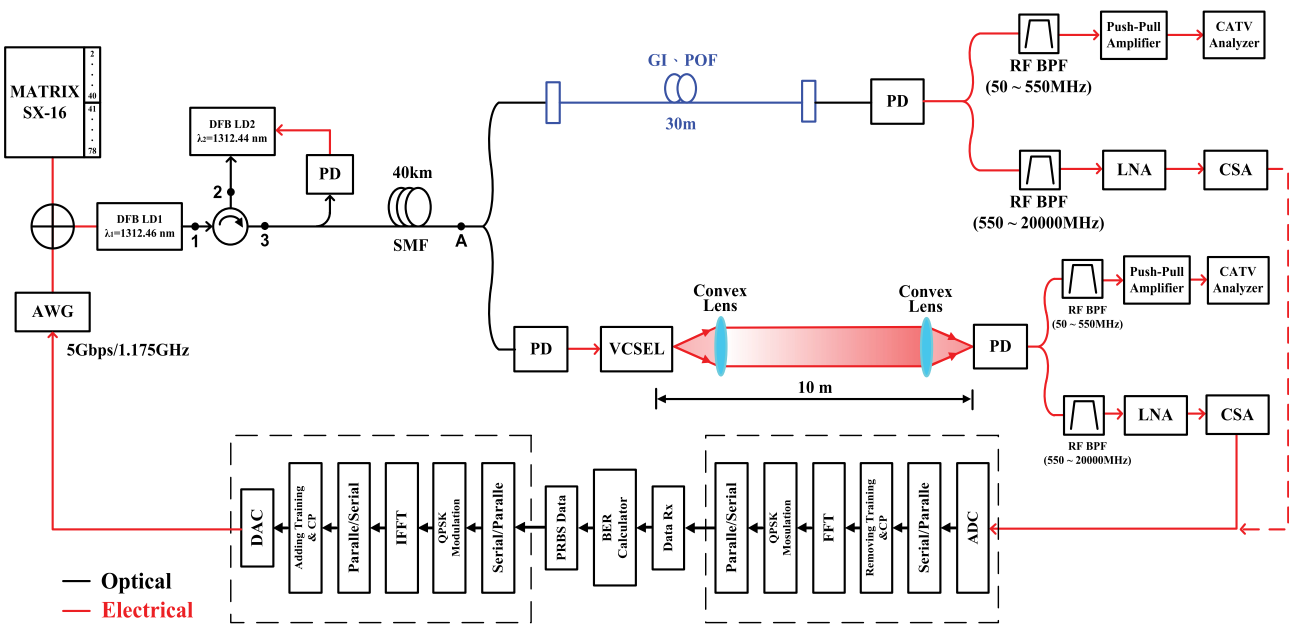


**Fig. 1** Experimental setup of our proposed hybrid CATV/16-QAM-Digital CATV/16-QAM-OFDM in-building networks over a combination of 40-km single-mode fiber (SMF) and 30-m gradient index-plastic optical fiber (GI-POF)/10-m visible light communication (VLC) transport.

(BER) performance analysis. Another optical signal is detected by a PD, and the detected RF signal is supplied to the vertical cavity surface emitting laser (VCSEL)-based VLC subsystem. The VCSEL, with a 3-dB modulation BW/wavelength range/color of 5.2 GHz/678 to 680 nm/red, is directly modulated by the detected RF signal. The output power and bias current of the VCSEL are 5.2 mW (conforming to the FDA Class IIIa mandatory limit) and 14 mA, respectively. After emission from the VCSEL, the light is diverged, launched into the convex lens, delivered in the free space, and then concentrated on a PD. The PD has a detection wavelength range of 350 to 1100 nm with a response of 0.65 mA/mW. Such a VLC subsystem has a total power loss (transmission loss + coupling loss) of about 4.5 dB. The distance between the VCSEL and PD is 10 m. After PD detection, the detected RF signal is split by a $1 \times 2$ RF splitter, passed through two separate RF BPFs, boosted by two separate amplifiers (push-pull amplifier and LNA), and eventually supplied to a CATV analyzer and an OFDM analyzer.

## 3 Experimental Results and Discussion

The rate equations for LD with light injection and optoelectronic feedback techniques are given by[12]

$$\frac{\partial n}{\partial t} = \frac{I}{eV} - \frac{n}{\tau_n} - G \cdot P + k_{\mathrm{loop}}[P(t-\tau) - P_{\mathrm{av}}], \tag{1}$$

$$\frac{\partial P}{\partial t} = \left(G - \frac{1}{\tau_p}\right)P + \frac{2}{\tau_g}\sqrt{PP_i}\cos(\theta), \tag{2}$$

$$\frac{\partial \theta}{\partial t} = -df + \frac{1}{2}\alpha(G - G_{si}) - \frac{1}{\tau_g}\sqrt{\frac{P_i}{P}}\sin(\theta), \tag{3}$$

where $n$ is the carrier density, $I$ is the slave pumping current, $V$ is the laser active volume, $\tau_n$ is the carrier lifetime, $G$ is the gain, $P$ is the photon density, $k_{\mathrm{loop}}$ is the feedback coefficient, $\tau$ is the delay of the feedback loop, $P_{\mathrm{av}}$ is the average photon density, $\tau_p$ is the photon lifetime, $\tau_g$ is the cavity transit time, $P_i$ is the external injection power, $\theta$ is the phase difference between salve and master lasers, $df$ is the frequency detuning, and $\alpha$ is the linewidth enhancement factor. The slave laser relaxation oscillation damping rate $\Gamma_f$ can be derived from the above rate equations. The optoelectronic feedback increases the stability of the LD when $\Gamma_f > \Gamma_o$ (damping rate as LD only with light injection), resulting in out-of-phase carrier reinjection. The laser resonance frequency $f_0$ can be stated as[13]

$$f_0^2 = \frac{g_0 P}{4\pi^2 \tau_p}, \tag{4}$$

where $g_0$ is the gain coefficient. Out-of-phase carrier reinjection increases the photon density, which leads to an improvement of laser resonance frequency. Figure 2 shows the frequency response measured respectively for free running, 4.8 dBm external injection, and both 4.8 dBm external injection and optoelectronic feedback. Among which, the DFB LD's frequency response is about 5 GHz under a free-running condition and 1.85 GHz for 4.8 dBm under an external injection condition, while it increased to 25.2 GHz under the conditions of both external injection and optoelectronic feedback. The 4.8-dBm external injection increased the frequency response of the laser by 3.7 times ($18.5/5 = 3.7$), while it increased the laser's frequency response by 5 times ($25.2/5 = 5.04$) under the conditions of both external injection and optoelectronic feedback.

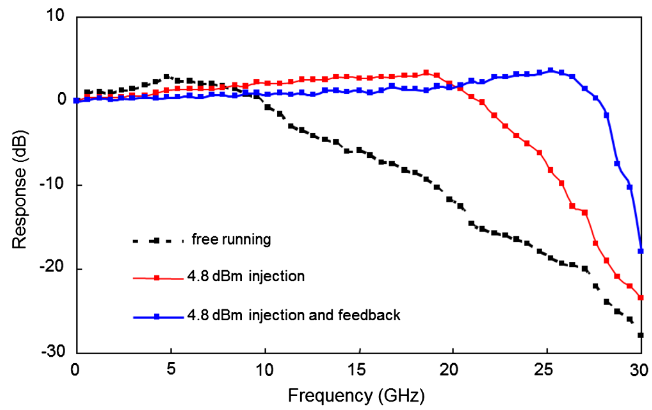


**Fig. 2** Frequency response of the distributed feedback laser diode (DFB LD2).

Figure 3(a) shows the electrical spectrum of the hybrid CATV/16-QAM-Digital CATV/16-QAM OFDM data signal over a 40-km SMF PON transmission in point A of Fig. 1. CATV and 16-QAM-Digital CATV signals have lower frequencies of CH 2 to 40 at 55.25 to 319.25 MHz and of CH 41 to 78 at 325.25 to 547.25 MHz. A 5 Gbps/1.175 GHz 16-QAM-OFDM has a bandwidth of 1.25 GHz, which denotes that the lowest frequency of a 5 Gbps/1.175 GHz 16-QAM-OFDM signal is 550 MHz ($1.175 - 1.25/2 = 0.55$ GHz) while the highest frequency is 1.8 GHz ($1.175 + 1.25/2 = 1.8$ GHz). The electrical spectrum of the hybrid CATV/16-QAM-Digital CATV/16-QAM-OFDM data signal after 40-km SMF PON transmission with a 1310-nm wave band light source is flatter than that with a 1550-nm wave band light source because nondispersion is absent in the 1310-nm wave band. The better the flat electrical spectrum is, the better the system transmission performance will be. Figures 3(b) and 3(c) show the electrical spectra of the hybrid CATV/16-QAM-Digital CATV/16-QAM OFDM signals over a combination of 40-km SMF and 30-m GI-POF/10 m VLC transport, respectively. Figure 3(b) clearly has a lower interference and better flat spectrum than Fig. 3(a), both of which result in better transmission performances. Increased transmission performances can be attributed to a lower total power loss of the VLC subsystem compared with that of the GI-POF one. A lower total power loss is related to a higher received optical power, which results in better transmission performances. Furthermore, although the mode dispersion tolerance of GI-POF is considerably higher than that of the multimode fiber, mode dispersion still exists in the GI-POF subsystem, resulting in greater performance degradation compared with the VLC one. The electrical spectrum is distorted by the spatial light beam expander and the transmission distance. Given that the digital signal is generally more robust than the analog signal with respect to noise and nonlinear distortion, the RF carrier level of the simulated 16-QAM digital CATV channel is approximately 10 dB, which is lower than that of the simulated analog CATV channel. As regards to the hybrid analog

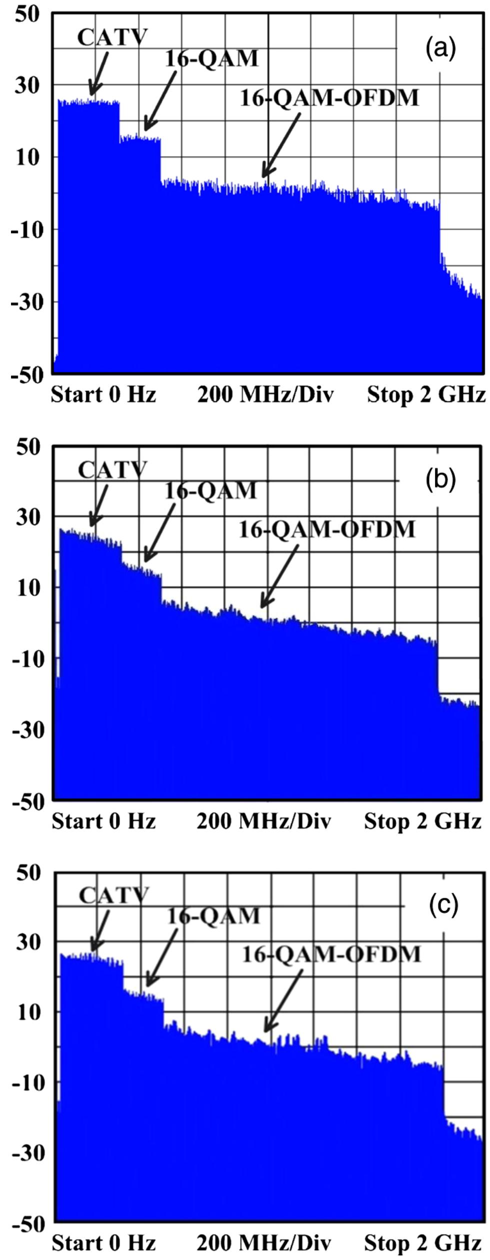


**Fig. 3** Electrical spectrum of the combined CATV, 16-QAM-Digital CATV, and 16-QAM-OFDM signals (a) over a 40-km SMF transport (measured at point A of Fig. 1), (b) over a 40-km SMF 30-m GI-POF transport, and (c) over a 40-km SMF 10-m free-space VLC transport.

and digital transmission, a CATV signal is set to a high power level to maintain the quality of analog transmission and the 16-QAM/16-QAM-OFDM signal is set to a low power level because the digital signal has a better tolerance for transmission.

The plotted CNR/CSO/CTB values and the measured CATV signal over a 40-km SMF PON transmission at point A of Fig. 1 are presented in Fig. 4. For a CATV signal over a 40-km SMF PON transmission without using injection-locked and optoelectronic feedback techniques, the free-running CNR/CSO/CTB values are greater than 48, 59, and 59.1 dB, respectively. In contrast, with the use of injection-locked and optoelectronic feedback techniques, the CNR/CSO/CTB values are maintained at ≥51.1, 62, and

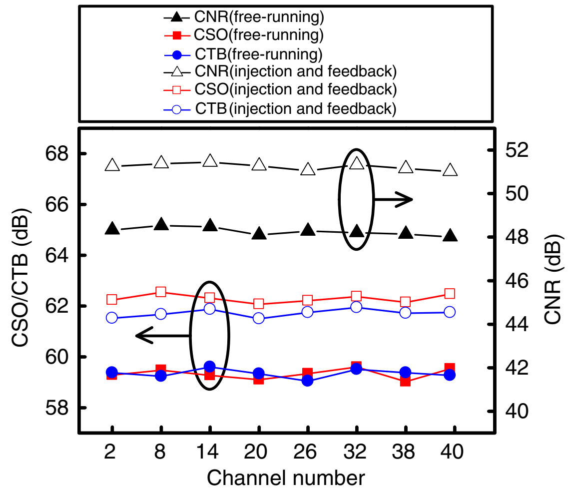


**Fig. 4** Measured CNR/CSO/CTB values under NTSC channel number (CH 2 to 40) over a 40-km SMF transport for free-running and with light injection and optoelectronic feedback cases.

61.7 dB, respectively, thus improving the performances of CNR/CSO/CTB values by approximately 3.1, 3, and 2.6 dB, respectively. Injection-locking behavior occurs when an injection source laser is slightly detuned to a frequency lower than that of the injection-locked laser. The injection-locked laser can be stably locked depending on frequency detuning. The optimal injection-locking condition is found when the detuning between the two DFB LDs is 0.02 nm. Otherwise, for CSO and CTB performances, the CSO and CTB values (≥62 and 61.7 dB, respectively) of systems with a 1310-nm nondispersion light source scheme are significantly improved. The improved results can be attributed to the use of a 1310 nm light source to achieve nondispersion in the SMF link. A system link with a transmission length of 40-km SMF has a positive dispersion of 680 ps/nm (17 ps/nm/km × 40 km), whereas a system link with a 1310 nm light source has zero dispersion. Combining the SMF and the nondispersion light source leads to zero total fiber dispersion. Low fiber dispersion results in low fiber-dispersion-induced distortions, which improve CSO and CTB performances.

The measured CNR values under NTSC channel number (CH 41–78) over a 40-km SMF PON transport for free running and with light injection and optoelectronic feedback cases are shown in Fig. 5. Clearly, the CNR value is increased as light injection and optoelectronic feedback techniques are employed. For the simulated digital 16-QAM signal transmission, the CNR values are about 38.6 dB (free running) and 41.1 dB (with light injection and optoelectronic feedback), respectively. Both values satisfy the minimum requirement of 30 dB for the 16-QAM signal with BER $<10^{-6}$.

To evaluate the transmitted 16-QAM-OFDM signal performance over 40-km PON transmission, the measured BER curves and constellation map at a data signal of 5 Gbps/1.175 GHz are presented in Fig. 6. At a PON transmission distance of 40 km, without employing injection-locked and optoelectronic feedback techniques, the received optical power level at the BER of $10^{-6}$ is −10 dBm. In comparison, with injection-locked and optoelectronic feedback techniques, the received optical power level at the BER of $10^{-6}$ decreases to −12 dBm. The improved power penalty of 2 dB indicates

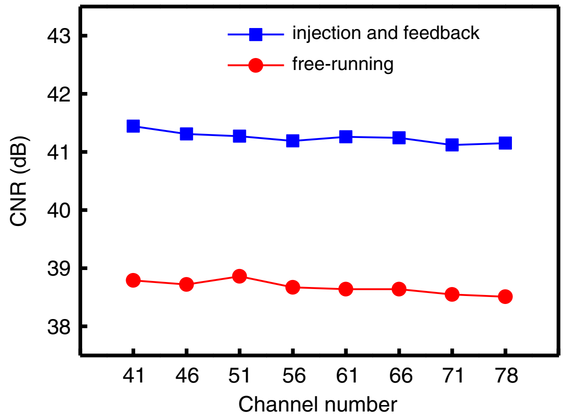


**Fig. 5** Measured CNR values under NTSC channel number (CH 41 to 78) over a 40-km SMF transport for free-running and with light injection and optoelectronic feedback cases.

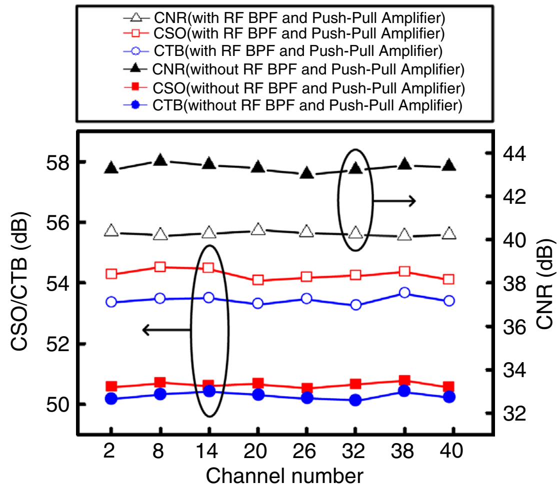


**Fig. 7** Measured CNR/CSO/CTB values under NTSC channel number (CH 2 to 40) over a 40-km SMF and a 30-m GI-POF transport.

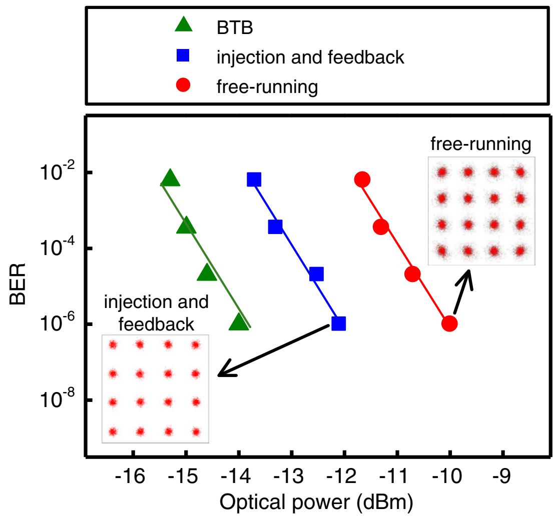


**Fig. 6** Measured bit error rate (BER) curves and constellation maps of 5 Gbps/1.175 GHz data signal over a 40-km SMF transport.

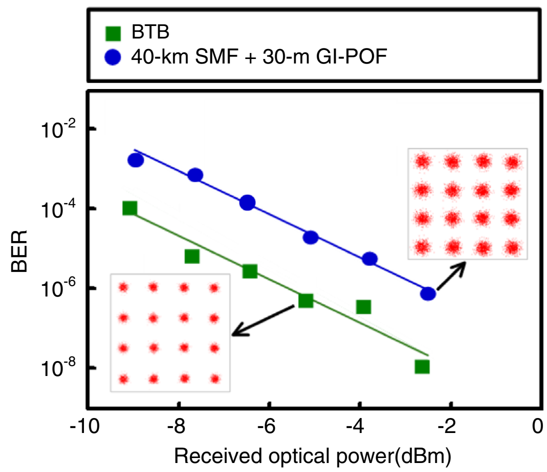


**Fig. 8** Measured BER curves of 5 Gbps/1.75 GHz 16-QAM-OFDM data signal over a 40-km SMF and 30-m GI-POF transport.

that employing injection-locked and optoelectronic feedback techniques are important to enhance the signal-to-noise ratio of the proposed system.

Figure 7 presents the measured CNR/CSO/CTB values over a combination of 40-km SMF/30-m GI-POF transport. Owing to the insertion loss of the push-pull amplifier and RF BPF, the CNR value of systems with the push-pull amplifier is degraded by about 3 dB compared with that of systems without the push-pull amplifier and RF BPF. However, systems with the push-pull amplifier and RF BPF still meet the CATV CNR performance demand at the subscriber (≥40 dB). For CSO and CTB performances, the CSO and CTB values (≥53/53 dB) of systems with the push-pull amplifier are obviously improved. Improved results are due to the use of the push-pull amplifier to suppress the distortions.[14]

The measured BER curves and constellation maps of 5 Gbps/1.175 GHz 16-QAM-OFDM data signal over a combination of 40-km SMF/30-m GI-POF transport are shown in Fig. 8. At a BER of $10^{-6}$, a power penalty of 2.7 dB is obtained. At a received optical power level of −2.8 dBm, the proposed GI-POF-based in-building networks can clearly provide good BER performance and a clear constellation map. Error transmission is achieved to demonstrate the feasibility of establishing such a hybrid CATV/16-QAM-Digital CATV/16-QAM-OFDM in-building network over SMF and GI-POF transport.

Figure 9 shows the measured CNR/CSO/CTB values over a combination of 40-km SMF/10-m VLC transport. The CNR value of systems with the push-pull amplifier and RF BPF is degraded by about 3 dB compared with that of systems without the push-pull amplifier and RF BPF. Such CNR degradation is due to the insertion loss of the push-pull amplifier and RF BPF. Nevertheless, the CNR value of systems with the push-pull amplifier and RF BPF still satisfies the CATV CNR requirement (≥43 dB). In contrast, the CSO and CTB values of systems with the push-pull amplifier are clearly improved. The CSO and CTB values of systems with the push-pull amplifier are higher than 54 dB, which meets the CATV CSO/CTB performance demands at the subscriber (≥53/53 dB). These improvement results are attributed to the use of the push-pull amplifier to eliminate distortions. Moreover, in comparing the CNR/CSO/CTB performances

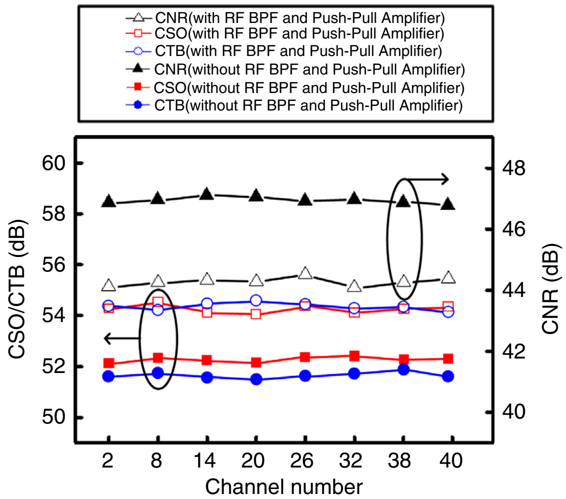


**Fig. 9** Measured CNR/CSO/CTB values under NTSC channel number (CH 2 to 40) over a 40-km SMF and a 10-m free-space VLC transport.

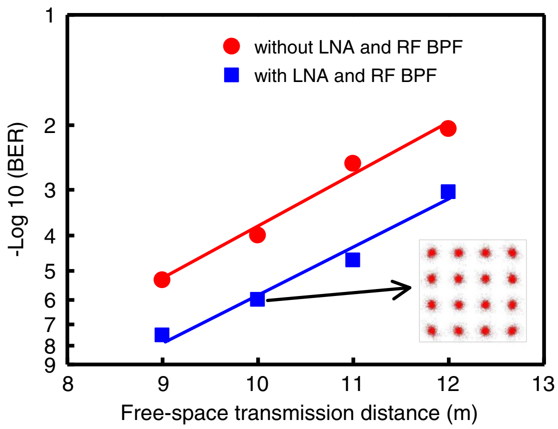


**Fig. 10** Measured BER curves of 5 Gbps/1.75 GHz 16-QAM-OFDM data signal over a 40-km SMF and 10-m free-space VLC transport.

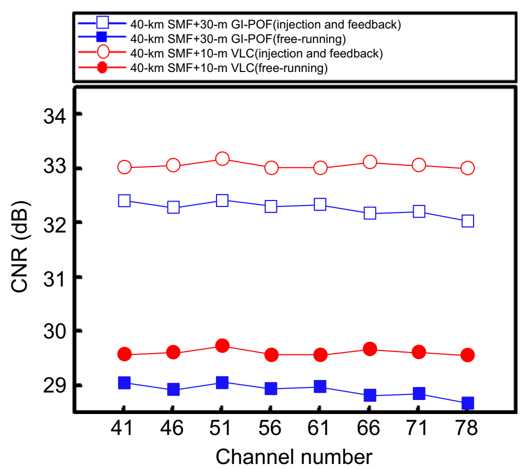


**Fig. 11** Measured CNR values under NTSC channel number (CH 41 to 78) over a 40-km SMF and a 30-m GI-POF/10 m free-space VLC transport.

of the GI-POF (Fig. 7) and VLC (Fig. 9) subsystems, the CNR/CSO/CTB performances of the GI-POF subsystem are obviously worse than those of the VLC one. The CNR/CSO/CTB degradations are due to high total power loss and mode dispersion of the GI-POF subsystem.

For the transmitted 5 Gbps/1.175 GHz 16-QAM-OFDM signal over 40-km SMF and 10-m free-space VLC transmission, the measured BER curves and constellation map versus transmission distance are shown in Fig. 10. When the free-space VLC transmission distance is fixed at 10 m, without employing LNA and RF BPF, the received BER at a free-space distance of approximately 10 m is $10^{-4}$. In contrast, when LNA and RF BPF are employed, the received BER at a free-space distance of approximately 10 m is $10^{-6}$. The improved BER from $10^{-4}$ to $10^{-6}$ is observed in a free-space VLC system because of noise suppression by LNA and noise removal by RF BPF.

The measured CNR values under NTSC channel number (CH 41 to 78) over a 40-km SMF and a 30-m GI-POF/10 m VLC transport are presented in Fig. 11. As the injection and feedback are employed simultaneously, CNR performance is improved around 3 dB. For the simulated digital 16-QAM CATV signal transmission, the CNR values are about 29 dB (free running) and 32 dB (injection and feedback), respectively. Both values meet the minimum demand of 30 dB for the 16-QAM signal with BER $<10^{-6}$.

## 4 Conclusion

A hybrid CATV/16-QAM-Digital CATV/16-QAM-OFDM in-building network based on a hybrid PON and GI-POF/VLC scenario is proposed and experimentally demonstrated. For a hybrid PON and GI-POF/VLC scenario, the combined CATV/16-QAM-Digital CATV/16-QAM-OFDM signals are broadcast to all subscribers after the signals are received by the PD. Thus not only do the CNR/CSO/CTB performances of the proposed in-building network satisfy the CATV requirements ($\geq 43/53/53$ dB) at the subscriber, but their BER value meets the high-quality 16-QAM-Digital CATV/16-QAM-OFDM demand ($<10^{-6}$) as well. The system offers complete broadband service for cable TV, telecom, and the Internet. It not only provides an integration of optical fiber backbone and indoor access, but also reveals its convenient last-mile application for final users, making it very appealing for advanced FTTH application.

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