100 GHz ultra-wideband (UWB) fiber-to-the-antenna (FTTA) system for in-building and in-home networks

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Abstract: Fiber-to-the-antenna (FTTA) system can be a cost-effective technique for distributing high frequency signals from the head-end office to a number of remote antenna units via passive optical splitter and propagating through low-loss and low-cost optical fibers. Here, we experimentally demonstrate an optical ultra-wideband (UWB) – impulse radio (IR) FTTA system for in-building and in-home applications. The optical UWB-IR wireless link is operated in the W-band (75 GHz - 110 GHz) using our developed near-ballistic unitraveling-carrier photodiode based photonic transmitter (PT) and a 10 GHz mode-locked laser. 2.5 Gb/s UWB-IR FTTA systems with 1,024 high split-ratio and transmission over 300 m optical fiber are demonstrated using direct PT modulation.

OCIS codes: (060.2330) Fiber optics communications; (060.4510) Optical communications.

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1. Introduction

As the bandwidth demand for Internet and home entertainment has increased exponentially in recent years, using fiber-to-the-home (FTTH) technology becomes a promising access solution. Passive optical network (PON) is a cost-effective FTTH network distributing broadband services to end-users using passive optical splitters. Nowadays, users not only require high bandwidth FTTH network, but also demand mobile services [1,2]. Ultra-wideband (UWB) has been considered as one of the promising techniques for wireless communications. It is also considered as a replacement for the high-definition (HD) video cables [3,4] in the near future. In the UWB-impulse radio (IR) system, each transmitted pulse occupies the whole UWB bandwidth. It is a carrier-less system, having a strong tolerance against multipath reflections and other signal interferences. The UWB-IR system is particularly suitable for high data rate and short-range in-building applications.

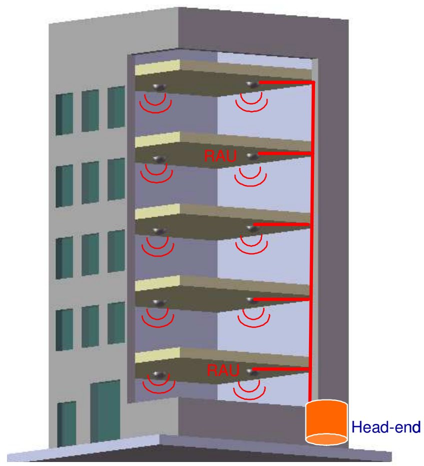

Fig. 1. Concept of UWB signal distribution in the FTTA system for in-building applications.

Using optical technology in UWB-IR system can be cost-effective and producing good quality signal when compared with electronic approach, since the optical approach can remove the high propagation loss and limited transmission distances when transmitting short electrical pulses in electrical cables. Figure 1 shows the conceptual architecture of the UWB signal distribution in the fiber-to-the-antenna (FTTA) system. A head-end office generates the UWB signals, which are distributed over low-loss and low-cost optical fibers to a number of subscribers (different apartments or different rooms inside an apartment). At the subscriber ends, the received optical UWB signals are radiated via an optical pulse triggered photonic transmitter (PT) to broadcast the UWB signals to the UWB-ready televisions or computers. In the FTTA system, modulation and complex electronic processing can be performed in the head-end office, while signals are radiated in the low-cost remote antenna units (RAUs). Due to the high atmospheric attenuation at high frequency bands, the cost-effective FTTA system can support a large number of RAUs to provide good wireless service coverage.

Previous techniques enable UWB system to support bit rates of up to 1 Gb/s at a few meters range [5], and extended range of 30 m by using multiple-input multiple-output (MIMO) technique [6]. Here, we demonstrated a 2.5 Gb/s UWB-IR high split-ratio FTTA system over 300 m optical fiber. The optical UWB-IR wireless link is operated in the W-band (75 GHz - 110 GHz) using our developed near-ballistic unitraveling-carrier photodiode (NBUTC-PD) [7] based PT [8] and a mode-locked laser with a 10 GHz repetition rate. 2.5 Gb/s UWB-IR FTTA systems are experimentally demonstrated in the 300 m fiber link when attenuation was > 30 dB, which corresponds to a split-ratio of 1,024. When compared with other optical UWB communication links [9,10], our scheme can be operated at a much higher

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data rate and without the need of radio-frequency (RF) mixer for the signal down-conversion at the receiver (Rx).

2. Device structure and experiment

Figure 2 shows top-view photograph of the NBUTC-PD based PT. The NBUTC-PD has an active area of 144 μm^2 connecting to a planar quasi-yagi antenna. Bond pads are used for flip-chip bonding process on a 100 μm thick aluminum-nitride (AlN) substrate for good thermal conduction. The optical signal is launched vertically onto the active area of the NBUTC-PD via a lens fiber. A W-band horn antenna is directly connected to the quasi-yagi antenna. A RF probe is used to bias and drive the PT in the case of direct modulation. Previous studies [7] showed that the proposed NBUTC-PD can work efficiently with a maximum saturation current of about 30 mA under continuous wave (CW) operation. However, the average saturation current will decrease under optical pulse launching (experiment reported in this paper, in which the NBUTC-PD is excited by impulse-radio signal). This is due the higher peak optical power will produce the space-charge screening effect and reduce the average saturation current.

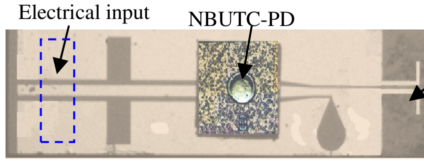

Fig. 2. Photograph of the novel W-band NBUTC-PD used for the UWB-IR system.

In the experiment, two scenarios of the FTTA systems were evaluated. Figure 3(a) shows the first scenario in which the optical UWB-IR signal is broadcast and distributed to multiple RAUs through optical fibers and passive fiber splitter. An optical pulse train at 10 GHz repetition rate was generated by a commercial fiber mode-locked laser (MLL) (*Calmar Laser, PSL-10-2T*). The pulse train was then encoded by 1.5 Gb/s non-return-to-zero (NRZ) data at pseudo-random binary sequence 2^{15}-1 produced by a bit-error-rate tester (BERT). There was no need of synchronization between the MLL and the BERT. The inset in Fig. 3 shows the autocorrelator trace of the optical pulse after amplified by an erbium-doped fiber amplifier (EDFA). The full-width half-maximum (FWHM) pulse width was 2.22 ps and this had the Fourier-transformed frequency component around 100 GHz, which was suitable for our designed NBUTC-PD and antenna operating at W-band (75 – 110 GHz).

The optical UWB-IR signal was distributed over 300 m of optical fiber (250 m of standard single mode fiber (SSMF) and 50 m of dispersion compensating fiber (DCF)). The dispersion parameter of the SSMF and DCF are 17 ps/nm/km and −100 ps/nm/km respectively. A variable optical attenuator (VOA) was used to emulate the achievable split ratio of the FTTA system. We measured that error-free BER operation can be achieved when the attenuator was > 30 dB, which corresponded to a split-ratio of 1,024. Finally the UWB-IR signal was launched into the NBUTC-PD via a lens fiber at the RAU, where the signal was radiated in the air via a W-band horn antenna. At the Rx side, another W-band horn antenna was used to receive the wireless signal. The received signal was first amplified by a W-band low noise amplifier (LAN), then it was envelope detect by a fast W-band power detector. The data was analyzed and BER measurements were performed. This scenario could emulate the case of downstream wireless signal broadcast from the head-end office to a large number of RAUs, where the UWB-IR signal are then transmitted to different end-users' devices wirelessly.

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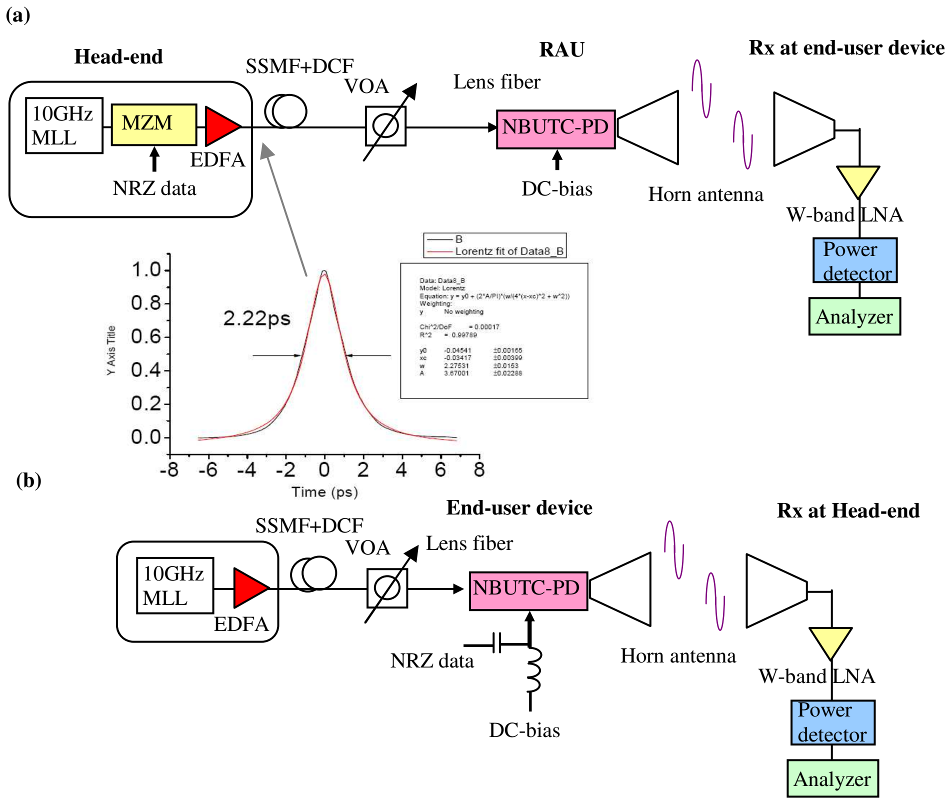

Fig. 3. Experimental setup of the UWB-IR FTTA system using (a) external modulation and (b) direct modulation. MLL: mode-locked laser, MZM: Mach-Zehnder modulator, SSMF: standard single mode fiber, EDFA: erbium doped fiber amplifier, VOA: variable optical attenuator.

We also tested another scenario of the optical wireless link as shown in Fig. 3(b). In this case, the optical pulse generated by the MLL was first distributed to the NBUTC-PD. The NBUTC-PD was directly modulated by a 2.5 Gb/s data (PRBS: 2^{15}-1) via a bias-tee. This could emulate the case for the upstream connection where each end-user has a low power 10 GHz optical source and transmits the upstream signal using direct modulation of the NBUTC-PD in their end-user devices.

3. Results and discussion

We first analyzed the operation frequency bands of the UWB-IR wireless signal emitted by the NBUTC-PD and the envelop-detected baseband signal at the Rx without the fiber transmission. Figures 4(a) and 4(b) show the received RF spectra measured at the Rx side in the FTTA system using direct modulation before and after the power detector, respectively. In order to measure the W-band signal, millimeter wave harmonic mixer was used to extend the frequency coverage of the RF spectrum analyzer. We can observe from Fig. 4(a) that the emitted UWB-IR wireless signal occupied mainly between 90 GHz to 110 GHz frequency band, with peak frequency at about 100 GHz. We can also observe from Fig. 4(b) that the power detector can successfully envelop-detect the UWB-IR signal; and a baseband spectrum of 2.5 Gb/s NRZ signal can be detected. However, when the fiber transmission distance increased (up to 250 m SSMF); chromatic dispersion broadened the optical pulse-width and the photo-generated UWB power envelope at 90-110 GHz disappeared. Hence 50 m DCF was used for dispersion compensation. Figures 5(a), 5(b), and 5(c), show the optical pulse shape detected at back-to-back, 250 m SSMF, and 250 m SSMF together with 50 m DCF

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respectively. A 50 GHz photodiode module (*Anritsu, MN4765A*) and a 50 GHz sampling scope were used. The system limited time resolution is ~12 ps. After 250 m SSMF fiber transmission [Fig. 5(b)], the FWHM pulse width broadened from less than 12 ps (system limited) to around 16 ps. The pulse width can be successfully compressed to around system-limited time resolution after the dispersion compensation [Fig. 5(c)].

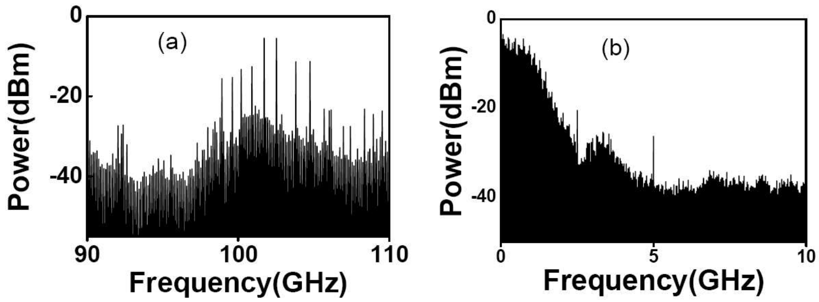
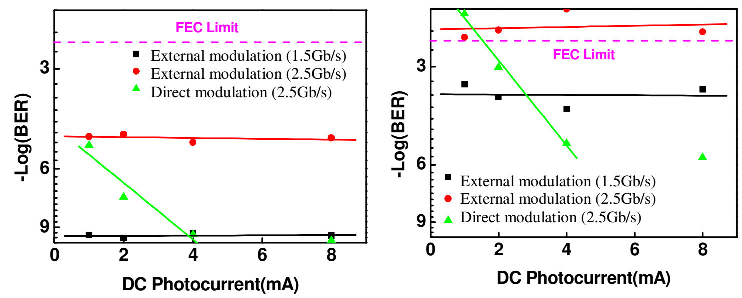


Fig. 4. Received RF spectra measured at the Rx side using (a) before and (b) after the power detector.

Fig. 5. The measured optical pulse by using 50 GHz photodiode (a) without fiber link, (b) 250 m SSMF, and (c) 250 m SSMF and 50 m DCF.

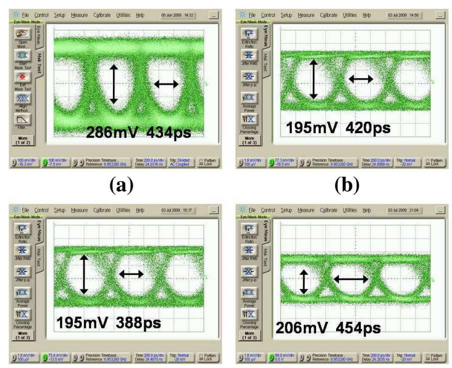
Then we evaluated the BER performance of the wireless transmission link of our UWB-IR FTTA system (250 m SSMF + 50 m DCF with 1,024 split-ratio) using external modulation [Fig. 3(a)] and direct modulation [Fig. 3(b)] at antenna-to-antenna wireless transmission distances 20 cm and 160 cm, respectively. In Fig. 6(a), we can observe that BER < 10^{-9} can be achieved at 2.5 Gb/s direct modulation, and BER below the forward-error-correction (FEC) level [11] at 2.5 Gb/s external modulation. As shown in Fig. 6(b), by increasing the wireless transmission distance to 160 cm, 2.5 Gb/s direct modulation can still be achieved below the FEC level, however, 2.5 Gb/s external modulation is not possible by increasing the photocurrent. At this case, we can decrease the data rate to 1.5 Gb/s in order to achieve the FEC level. It is also worth to mention that in the wireless link, we are using the NRZ on-off keying (OOK) modulation, which is considered by companies as one of the promising modulation formats for in-building wireless applications due to the simple circuitry in signal generation and detection; and low power consumption of non-coherent detection at the Rx (can be envelop-detected). Thus, phase noise of local oscillator has no effects on the detection performance.

We also compared the received error-free (BER < 10^{-9}) eye patterns at 1.5 Gb/s (antenna-to-antenna distance was 20 cm). Figures 7(a) and 7(b) show the detected 1.5 Gb/s eye patterns of external modulation at back-to-back and after 250 m SSMF with 50 m DCF transmission, respectively. The clear eye opening shows that the DCF can successfully dispersion compensate the optical signal. Figures 7(c) and 7(d) show the detected 1.5 Gb/s eye patterns after > 30 dB attenuation of optical power with transmission of 250 m SSMF and 50 m DCF by using external modulation and direct modulation respectively. We can clearly see that even under 1,024 split-ratio (>30dB attenuation), both modulation schemes can support clear eye opening at 1.5 Gb/s.



(a) **(b)**

Fig. 6. Measured BER vs. photocurrent at antenna-to-antenna wireless transmission distances of (a) 20 cm and (b) 160 cm.



(a) **(b)** **(c)** **(d)**

Fig. 7. Measured 1.5 Gb/s eye patterns at (a) back-to-back with external modulation, (b) 250 m SSMF + 50m DCF with external modulation, (c) 250 m SSMF + 50m DCF with 1,024 split-ratio, external modulation and (d) 250 m SSMF + 50m DCF with 1,024 split-ratio, direct modulation. The antenna-to-antenna transmission distances are 20 cm.

4. Conclusion

We have experimentally demonstrated an optical UWB–IR FTTA system for in-building and in-home applications using the NBUTC-PD based PT and a 10 GHz mode-locked laser. The UWB-IR wireless link was operated from 75 GHz to 110 GHz, having a peak RF power at about 100 GHz. Two scenarios of the FTTA system were evaluated, emulating the downstream and upstream FTTA systems. 2.5 Gb/s UWB-IR FTTA systems having high split-ratio of 1,024 and transmission over 300 m optical fiber were demonstrated.

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