Optics Communications 356 (2015) 451–455

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Hybrid intensity-modulation-to-phase-remodulation optical wavelength reuse transport system

Ching-Hung Chang*, Meng-Chun Tseng, Cheng-Han Tseng

Department of Electrical Engineering, National Chiayi University, Taiwan

ARTICLE INFO

Article history:
Received 23 July 2015
Received in revised form
18 August 2015
Accepted 19 August 2015

Keywords:
Radio-over-fiber (RoF)
Phase modulation (PM)
Intensity modulation (IM)
Wavelength reuse
Vertical-cavity-surface-emitting laser (VCSEL)

ABSTRACT

A hybrid intensity-modulation (IM)-to-phase-remodulation optical wavelength reuse transport system is proposed and demonstrated experimentally. Based on the transport system, an optical carrier can be intensity-modulated with an orthogonal frequency-division multiplexing (OFDM) signal and then phase-remodulated with a radio frequency (RF) signal prior to communicating its destination through a span of single mode fiber. The OFDM signal at the receiver end can be directly detected using a photodetector (PD), and the phase-modulated RF signal can be detected by another PD after being converted back to intensity-modulation format by a semiconductor laser. In this study, the working window of the semiconductor laser-composed phase-modulation-format-to-IM-format converter is not fixed. The converter can be flexibly adjusted to align with the wavelength of the employed optical carrier. Experimental results prove that both OFDM and RF signals can be clearly detected with an error-free transmission. Evident interference is not found between both signals at the receiver end.

1. Introduction

Following the development of fiber optical communication industry, various radio-over-fiber (RoF) techniques and fiber-to-the-home (FTTH) transport systems have been proposed and demonstrated to provide high capacity and low attenuation transmission links for subscribers [1,2]. To employ the transmission potential of optical fiber fully and to satisfy the tremendous demand of mobile services and broadband wireline services simultaneously, integrating both RoF and FTTH signal transmissions in a single transport system is highly developed [3,4]. Traditionally, such integration system can be achieved by modulating RoF and FTTH signals individually in two different optical carriers before being transmitted to the receiver end [5]. The interference between the two signals is ignorable because the signals in a hybrid transport system are far from each other in frequency domain. This method is simple and straightforward. However, additional optical wavelength separators or selectors, such as arrayed waveguide grating and optical bandpass filter (OBPF), must be inserted to separate the optical carriers into different receiver circuits. The number of supportable clients is divided because each end user utilizes two optical carriers to deliver his data. These limitations are overcome by developing and employing wavelength reuse schemes to deliver both RoF and FTTH signals by a single lightwave [6–8]. In [9,10], an optical lightwave is intensity modulated with a RoF signal prior to communicating to a base station (BS). When the lightwave arrives at the BS, the central carrier of the downstream lightwave is withdrawn by a fiber Bragg grating (FBG) and then reused to intensity-remodulate with a baseband signal for upstream transmission. In this case, the downstream RoF signal does not interfere with the upstream signal because the RoF signal is not transmitted at the central carrier of the optical lightwave. When the remained optical sidebands of the downstream lightwave are simultaneously detected by a photodetector (PD), the central frequency of the RoF signal can be doubled. Such optical frequency up-conversion process is proved to be a useful method to transmit and promote the frequency band of next generation wireless communications via relative low frequency electrical devices in a central office. For example, the downstream signals in [11] are modulated as orthogonal frequency division multiplexing (OFDM) modulation format and are individually modulated with multiple coherent optical tones before being communicated to BSs. Once if two of the optical tones are selected by a wavelength selective switch and detected simultaneously by a PD, the central frequency of the OFDM signal can be promoted to the range equal to the frequency detuning of these two optical tones; hence different frequencies can be obtained to support different wireless networks. Similarly, the OFDM signal in [12] is modulated with an optical carrier and communicated to BSs and optical network units (ONUs) via an optical fiber transport system. The downstream lightwave can be detected for wireline application in the ONUs and be employed for high frequency wireless application in the

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* Corresponding author.
E-mail address: chchang@mail.ncyu.edu.tw (C.-H. Chang).

http://dx.doi.org/10.1016/j.optcom.2015.08.057
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BSs where the downstream lightwave is combined with a lightwave generated by an optical local oscillator before being detected by a PD. The wireless transmission frequency can be flexible adjusted by fine tuning of the optical local oscillator. This kind of optical frequency up-conversion process is widely employed in hybrid RoF and FTTH transport systems. However, if the wavelength of the employed optical coherent tones or optical carrier is shifted by temperature or other effects, the wavelength selector in [11] may not be able to achieve its functionality properly and the central frequency of the wireless signal in [12] may not be fixed, resulting in a failed RoF transmission.

In parallel with employing intensity-modulation (IM)-to-intensity-remodulation (IrM) schemes to reuse one optical lightwave, using the amplitude and phase of an optical carrier to deliver both signals individually is also proposed and developed recently [13–16]. If both signals are modulated with two different factors of an optical carrier, they can be accepted directly by the receiver. For example, in [14, 15], the amplitude of an optical carrier is initially modulated with one signal by an intensity modulator, and its phase is then remodulated with another signal by a phase modulator; similarly, the optical carrier in [16] is phase-modulated with one signal and then intensity-remodulated with another. Both IM to phase remodulation (PrM) and phase modulation (PM) to IrM are more flexible and superior than IM to IrM because this remodulation is colorless. No optical wavelength selector or separator must be placed prior to the second modulator, and the interference between the first and second signals is ignorable. The main drawback of utilizing the PM scheme is the required insertion of an additional device in front of the photodetector (PD) of the receiver. The additional device converts the optical lightwave from PM to IM format because the general PD can detect only the intensity variation of an inserted optical carrier. The phase state of the carrier is not identified by the PD. The additional device can be a delay interferometer (DI), an OBPF, or a FBG [17–19]. The DI is a colorless but an expensive device. Each DI only works for certain RoF signals whose frequency is located within the designed range. Employing a DI to finish the PM to IM format conversion is not flexible and economic. Comparably, employing OBPF or FBG to achieve the conversion is a relatively cheaper method. However, if the frequency of the phase-modulated radio frequency (RF) signal is changed or the wavelength of the employed optical carrier is slightly changed by temperature or other effects, the OBPF- and FBG-based conversion methods may not be able to perform their task properly, and the transmission performance may not be ensured.

In our early research [20], a flexible optical PM-format-to-IM-format converter is proposed and experimentally demonstrated based on a vertical-cavity surface-emitting laser (VCSEL). The conversion function is achieved by converting the phase-modulated RoF signal from optical double-sideband to optical signal sideband with carrier (OSSBC) format, and the detuning range of the converter is 3 nm. A hybrid IM-to-PrM optical wavelength reuse transport system is proposed and experimentally demonstrated based on the VCSEL-composed converter to promote the research outcome for optical wavelength reuse transport system. In the proposed system, the downstream optical carrier is intensity-modulated with an orthogonal frequency-division multiplexing (OFDM) data stream and then phase-remodulated with another RoF signal before being transmitted to its destination. The power consumption and non-linear noises caused by high peak-to-average power ratio (PAPR) in downstream optical carrier is reduced efficiently [21] by modulating the OFDM data stream as quadrature phase shift keying (QPSK) modulation format; this IM-to-PrM modulations can efficiently reduce certain non-linear effects, such as self-phase-modulation (SPM) and cross-phase-modulation (XPM) [22,23]. The transmission performance of the hybrid IM-to-PrM optical wavelength reuse transport system is confirmed by low bit error rate (BER) values and clear eye and consternation diagrams.

2. Experimental setup

The schematic of the proposed hybrid IM-to-PrM optical wavelength reuse transport system is illustrated in Fig. 1. A 312 Mbps/1.25 GHz OFDM data stream with QPSK modulation format, which was generated by Matlab digital signal processing program and arbitrary waveform generator (AWG), was employed to drive a distributed feedback (DFB) laser diode directly. The inset of the Fig. 1 shows the block diagram of the OFDM transmitter, which consists of serial-to-parallel conversion, quadrature phase-shift keying (QPSK) modulation, inverse fast Fourier transform (IFFT), cyclic prefix (CP) insertion, and digital-to-analog conversion (DAC). The IFFT size is 512 and the sampling rate and digital-to-analog converter resolution of the AWG are 10-GS/s and 8 bits, respectively. The DFB output lightwave was then fed into a polarization controller prior to remodulating with a RF signal through a phase modulator. Here, the RF signal was composed by mixing a 200 Mbps non-return-to-zero data stream with a 10 GHz RF carrier. The hybrid signal was subsequently transmitted through a 25 km single mode fiber and split by a 50:50 optical splitter prior to the receipt of both OFDM and RoF receivers. Inside the OFDM receiver, the transmitted OFDM signal was directly converted back into electrical domain by a PD. The obtained OFDM waveform is captured by a real-time scope (Tektronix CSA 7404B) with a 20-GS/s sampling rate and a 3-dB bandwidth of 4-GHz and is demodulated using an off-line Matlab digital signal processing program. In parallel, when another half of the downstream lightwave was fed into the RoF receiver, it was injected into and reflected back from a VCSEL through an optical circulator prior to the detection of a PD. The functionality of the VCSEL here was to convert the transmitted RoF signal from PM to IM format by converting the injected lightwave from DSB to OSSBC format. The obtained RF signal was then down-converted by mixing with a 10 GHz sinusoidal signal, and the redundant signals were filtered using an electrical low-pass filter. The obtained baseband signal was detected by a bit-error-rate tester and a digital communications analyzer.

3. Experimental results and discussions

In an optical fiber transport system, numerous factors, such as optical power fluxion, optical receiver power, and noise level, alert the overall system performance. For the OFDM signal transmission, the signal-to-noise ratio (SNR) is in inverse proportion to the PAPR value [25]. When QPSK modulation scheme is employed by each OFDM subcarrier, each subcarrier can have a constant power level. Consequently, a small PAPR value is produced for the entire OFDM signal; thus, a better SNR performance is expected. Although the downstream optical carrier had been phase-remodulated with RoF signal before being detected by the OFDM receiver, the effect of the RoF signal is ignorable because the PD inside the OFDM receiver can detect only the intensity fluctuation status of the downstream lightwave; it cannot detect the phase-modulated RF, so the OFDM receiver can only produce the transmitted OFDM signal. In Fig. 2(a), the electrical spectrum of the received OFDM signal is clearly presented.

Half of the downstream optical carrier is fed into a VCSEL prior to the detection of a PD to determine the phase-modulated RoF signal properly. Here, the VCSEL driving current is carefully adjusted to align the VCSEL lasing wavelength with the +1 sideband of the inserted lightwave so that the photon of the injected +1