DSBCS modulation scheme for hybrid wireless and cable television system

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Abstract: This work develops and demonstrates a double sideband with optical carrier suppression (DSBCS) modulation scheme for a hybrid wireless and cable television system based on a phase modulator (PM) and a polarization beam splitter (PBS). A carrier suppression ratio greater than 20 dB is achieved between two sidebands. In addition, the values of carrier-to-noise ratio, composite second-order and composite triple beat in various channels after 25 km of transmission are higher than the threshold value, and the power penalty of microwave signal in back-to-back and 25 km transmission perform well. Additionally, the constellation diagram of upstream signal is successfully recovered. Above results demonstrate that the proposed scheme is highly promising for practical applications.

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References and links

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1. Introduction

Radio-over-fiber (ROF) technology has received considerable interest recently owing to its potential applications in broadband wireless access networks [1–8]. Among the many advantages of this technology include enhanced microcellular coverage, easy installation, high capacity, low cost, and low power. Optical microwave generation is the conventional approach in ROF transport systems. Previous works have demonstrated the effectiveness of an optical carrier using external modulator based on double sideband (DSB), single-sideband (SSB), and DSB with optical carrier suppression (DSBCS) modulation schemes. DSB modulation incurs performance-fading problems due to the fiber dispersion, resulting in degradation of the receiver sensitivity. Although it’s capable of reducing the impairment of fiber dispersion, SSB modulation suffers from worse receiver sensitivity than DSB modulation [9]. Previous works have demonstrated that DSBCS modulation has the lowest spectral occupancy, lowest bandwidth requirement for radio frequency (RF) signal, and smallest power penalty of receiver sensitivity after long transmitted distances [10,11]. However, in radio-over-fiber links, the use of a modulator is limited mainly by the need for a complex electrical circuit to control the direct current (DC) bias and a high insertion loss, subsequently raising manufacturing costs. Given the above limitations of DSBCS schemes, some researchers have modulated the RF signals in an optical DSB format and then removed the optical carrier by using optical narrow-band filters [12–14]. However, the optical narrow band filters in that system will limit its applications.

This work demonstrates the feasibility of DSBCS scheme for a hybrid cable television (CATV) and wireless transport system based on phase modulator (PM) by undertaking two experiments. The first experiment verifies the ability of utilizing a PM and a PBS to achieve a colorless DSBCS scheme. Characterized as bias-free control, a PM has a significantly lower $V_{\pi}$ and less insertion loss than those of a Mach-Zehnder modulator (MZM). Moreover, comparing with the published DSBCS schemes which the central carrier is removed by using an optical filter (OF) or a fiber grating (FG), the proposed methodology is much more efficient and flexible since the employed PBS is a colorless device. The proposed scheme is free from the bandwidth limitations and wavelength alignment problems, which will significantly impact those OF- and FG-based DSBCS modulation schemes. In this experiment, a carrier suppression ratio greater than 20 dB is achieved among the carrier and the first order sidebands; in addition, a 7.5 GHz signal is up-converted colorlessly to 15 GHz. The second experiment involves directly feeding the CATV signals into a distributed feedback laser diode (DFB LD) and externally re-modulated the DFB LD output carrier with a 200Mbps/7.5GHz RF signal using a PM. Consequently, the hybrid CATV and RF signals are experimentally transmitted over a span of 25 km single-mode fiber (SMF). To construct a bidirectional link, an uplink signal is re-modulated with the downstream carrier based on the proposed scheme. The microwave transmission performances are evaluated and verified by error free transmission and clear eye diagrams.
2. Experimental setup

Figure 1 shows a microwave transport system developed in this work to demonstrate the feasibility of using a PM and a colorless PBS to achieve optical DSBCS format. In this system, an optical carrier is generated by a LD. To optimize the system performance, the LD output is bridged to a PM via a polarization controller (PC). Subsequently, the PM is modulated with a 7.5 GHz RF signal. Here, the polarization state of the input light wave is rotated at an angle of $45^\circ$ to the principal axis of the PM, so the RF signal can equally excite the polarization states of the PM output light wave into two orthogonal modes. In the principal axis of the PM, a double sideband with an optical carrier suppression modulation scheme is used [15]. The polarization beam splitter (PBS) is then connected at the output of the PM. At the two outputs of the PBS, the sidebands were via to the x axis output port and the central carrier was via to the y axis output port, respectively. The output optical signals of the PBS x and y axes are connected to an optical spectrum analyzer.

The PM output spectrum is shown in Fig. 1(a). The optical spectra of the separated sideband and carrier are shown in Figs. 1(b) and 1(c), respectively. Since the PBS is a colorless device, no matter what the applied optical wavelength is, the sideband and carrier can be separated easily and clearly. As shown in the Fig. 1(b), the carrier suppression ratio is larger than 20 dB and the spacing between two first order sideband is 15 GHz which is double
of the applied local oscillator (LO) frequency (7.5 GHz). According to the research outcomes of the [15], if the modulation index is set to around 2.39 ~2.43, an optimized optical carrier suppression ratio would be generated. Therefore, to maximum the DSBCS performance, the dynamic range is limited around the values making the PM with a modulation index between 2.39 and 2.43. As shown in the Fig. 1(c), the power variation among the central carrier and the first order sideband is significantly increased from 13.7 dB to 27.5 dB.

3. Experimental results and discussions

Figure 2 shows the schematic diagram of the proposed hybrid microwave transport system. The continuous wave (CW) laser is generated by a DFB LD. The CATV signal is directly modulated on a DFB LD, and then via a PM. The modulated signal is transmitted through a 25 km SMF and then via an optical coupler (OC). One path is received by a CATV analyzer, while the other path is transmitted to the PBS. Next, the modulated light waves are separated into two different paths by using the PBS. This work evaluates the transmission performance of the proposed scheme by simulating multi-carrier CATV signals through the generation of 33 NTSC-channels (547.25-739.25 MHz) by a Matrix SX-16 signal generator. The electrical spectrum of CATV is shown in Fig. 3(i). These 33 channels are directly fed into a laser diode with a central wavelength of 1549.4 nm and a threshold current of 75 mA. Next, the optical carrier passes through a polarization controller (PC) to control its polarization state before being re-modulated with a RF signal by using a PM. Here, the RF signal is composed by mixing a 200 Mbps non-return-to-zero (NRZ) data stream with a 7.5 GHz RF carrier. The hybrid CATV and RoF signals are transmitted through a 25 km SMF for downstream transmission, as shown in Fig. 3(a). In the receiver end, the CATV signal is separated by a 1 × 2 optical coupler. One copy of the downstream signal is received by a CATV receiver and analyzed by a CATV analyzer. Another one is passed through a PBS, which is used to divide the modulated light waves into two different paths. Figures 3(b) and 3(c) show the optical
spectra of the separated x and y axes, respectively. The x axis output signal is detected by a 20 GHz broadband photodiode (PD).

Fig. 3. The measured optical spectra and electric spectra diagrams.

Fig. 4. Measured CNR values under various CATV channels.

Fig. 5. Measured CSO values under various CATV channels.
Figure 3(ii) shows the electrical spectrum of the detected double frequency RoF signal. Next, the RF signal is down-converted by mixing with a 15 GHz RF carrier and filtered by an electrical low-pass filter (LPF). The demodulated signal is detected by a bit-error-rate tester (BERT) and a digital communications analyzer (DCA). In the upstream path, the central carrier emitted from the PBS y axis output is re-used and an orthogonal frequency-division multiplexing (OFDM) signal is re-modulated with it by an intensity modulator. Subsequently, the upstream signal is transmitted through another 25 km SMF span to return. Figure 3(iii) shows the electrical spectrum of the received OFDM signal. The inset of Fig. 2 shows the OFDM transmitter, which consists of serial-to-parallel conversion, 16-Quadrature Amplitude Modulation (16-QAM), inverse fast Fourier transform (IFFT), cyclic prefix (CP) insertion, and digital-to-analog conversion (DAC). The sampling rate and digital-to-analog converter resolution of the arbitrary waveform generator (AWG) are 10-GS/s and 8 bits, respectively. The IFFT size is 256. Notably a 1.25 GB/s OFDM signal with 8 subcarriers and occupying a total bandwidth of 312.5 MHz can be generated. In the OFDM receiver, the waveform is captured by a real-time scope (Tektronix® CSA 7404B) with a sampling rate of 20-GS/s and a 3 dB bandwidth of 4 GHz. The inset of Fig. 2 also shows the block diagram of a typical OFDM receiver. Additionally, the OFDM signal is demodulated using an off-line Matlab® digital signal processing program.

In the CATV transport system, Fig. 4 shows the carrier-to-noise ratio (CNR) performance of the system in various CATV channels. As the main parameter of the CATV broadcast system, CNR is estimated by measuring the peak amplitude of the video carrier and the noise floor level. The theoretical expression for CNR is [18]

\[
CNR = \frac{(mI)^2}{2B[N_{\text{thermal}} + N_{\text{laser}} + N_{\text{nonlinear}}]} \tag{1}
\]

where \(m\) denotes the optical modulation index; \(I\) represents the optical current; \(B\) refers to the bandwidth per channel of CATV; \(N_{\text{thermal}}\) denotes the photodiode shot noise and the receiver amplifier thermal noise; and \(N_{\text{nonlinear}}\) represents the noise generated by the nonlinear medium. The main noise is relative to the intensity noise from a laser. The CNR value should exceed 43 dB on the user’s premises to prevent “snow” from being present in the channel. Figure 4 plots the measured CNR for 0 km and 25 km transmission, respectively. The measured CNR in various CATV channels are higher than the threshold value. Comparing the 0 km transmission measurements reveals that a power penalty of approximately 2 dB for CNR values is presented at the 25 km transmission, due to a lower received power. Figures 5 and 6 show the system of composite second-order (CSO) and composite triple beat (CTB) as well as...
the corresponding performance in various CATV channels, respectively. To ensure an
acceptable quality of service (QoS), the CSO and CTB values should exceed 53 dB at the
consumer’s premises. CSO and CTB distortions are given by [18]

\[
CSO = 10 \log \left[ \frac{mD\Delta \lambda}{4c} \sqrt{16(\Delta \tau)^2 + \frac{4\Delta \lambda^2}{c^3} f^6} \right] + 10 \log N_{CSO} + 6 \tag{2}
\]

\[
CTB = 10 \log \left[ \frac{9m^2 D^2 \Delta \lambda^2}{4c} \left(4(\Delta \tau)^2 + 4\Delta \lambda f \right) \right] + 10 \log N_{CTB} + 6 \tag{3}
\]

where \(m\) is the optical modulation index; \(D\) is the dispersion coefficient; \(\Delta \lambda\) represents the
optical carrier wavelength; \(L\) is the fiber length; \(f\) is the CATV channel carrier frequency;
\(\Delta \lambda\) is the spectral width; \(\Delta \tau\) is the fiber dispersion, and \(N_{CSO}\) and \(N_{CTB}\) are the product
counts of CSO and CTB distortions, respectively. According to the Eqs. (2) and (3), the CSO
and CTB values will be affected not only by the product counts of the CSO and CTB
distortions but also by the fiber dispersion. The accumulated long-distance fiber dispersion
will cause the CTB a worse value than the CSO. According to Figs. 5 and 6, the measured
CSO and CTB values are higher than 53 dB, indicating that the obtained performance
satisfies the requirements for fiber optical CATV [18]. In the optical CATV transport system,
a larger modulation index value will generate a better CNR performance. However, the
product count of the CSO and CTB distortions will also be boosted up by the enlarged CATV
powers and thus worse the overall CSO and CTB performances. In order to optimize the
CNR, CSO and CTB performance, the optical modulation index (OMI) is about 4% per
channel.

In the wireless transport system, Fig. 7 shows the measured bit error rate (BER) values
and relative eye diagrams of the transmitted 200 Mbps signal with and without CATV in
back-to-back (BTB) and 25 km transmission scenarios. All of the eye diagrams are clear and
open. The power penalty for CATV off and CATV on can be neglected, and the power
penalty of RF signal in BTB and 25 km transmission also has a good performance.
Additionally, the transmitted 16-QAM OFDM signal performance is evaluated by the BER
curves and constellation maps, as shown in Fig. 8. At a BER of \(10^{-9}\), the power penalty
between CATV off and CATV on is smaller than 1 dB; in addition, the power penalty
between BTB and 25 km transmission of around 2 dB is presented.

**Down link**

![Fig. 7. Measured BER curves and eye diagrams.](image-url)
4. Conclusion

This work presents a double sideband with optical carrier suppression modulation scheme for a microwave transport system based on a phase modulator and a polarization beam splitter. Via the assistance of the polarization beam splitter, the sideband and carrier can be distinguished from each other to achieve optical double frequency applications and devise an amplitude re-modulation scheme. In addition to complying with CATV requirements where excellent performances of CNR, CSO and CTB are obtained for CATV signals, the proposed transport system satisfies the demand for high-quality wireless signal transmission over a 25 km SMF.

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