Four-User ~3-GHz-Spaced Subcarrier Multiplexing (SCM) Using Optical Direct-Detection via Hyperfine WDM

Shijun Xiao, *Student Member, IEEE,* and Andrew M. Weiner, *Fellow, IEEE*

***Abstract*—We demonstrate an error-free four-user ~3-GHz-spaced subcarrier multiplexing (SCM) experiment, where, for the first time to our knowledge, we use optical direct-detection via optical hyperfine wavelength-division multiplexing instead of heterodyne beating detection that is conventional for SCM. A hyperfine optical blocking filter allows optical single-sideband modulation with strong carrier suppression $\geq$20 dB below the unsuppressed single sideband and strong sideband suppression $\geq$20 dB.**

***Index Terms*—Analog fiber links, hyperfine wavelength-division multiplexing (HWDM), subcarrier multiplexing (SCM), ultra-dense wavelength-division multiplexing.**

SUBCARRIER multiplexing (SCM) is a scheme in radio-fiber links [1], [2], which exploits the use of mature microwave signal processing techniques, where multiple signals are multiplexed in the microwave domain and transmitted by a single optical carrier. Generally, microwave devices have several advantages over optical devices: the stability of oscillators, the frequency selectivity of filters, and the ease of implementing advanced modulation formats. The conventional SCM detection scheme uses heterodyne beating between the transmitted optical carrier and transmitted subcarriers in a high-speed photodiode (PD) followed by microwave power splitting and microwave mixing with microwave oscillators. In order to increase the spectral efficiency and the fiber chromatic dispersion tolerance, instead of optical double sideband (O-DSB), optical single sideband (O-SSB) modulation with partial carrier suppression has been widely used. Despite these advantages gained by the use of mature microwave techniques, SCM also has several drawbacks. These include: the need for the PD and microwave components to operate fast enough to handle the highest subcarrier frequency (which is well above the individual channel data rate); the electrical splitting loss in the receiver; and the sensitivity to fiber polarization-mode dispersion (PMD), which misaligns the carrier and subcarriers' polarization causing the fading of the heterodyne beat.

Optical direct detection by optical filtering was theoretically analyzed in SCM systems to alleviate the electronic bandwidth limit and experimentally demonstrated for a single SCM channel [3], [4]. However, no multiple-channel system experiments have been discussed due to the requirement for very narrow multiple channel optical filtering. Here, for the first time to our knowledge in experiments, we demonstrate a hybrid SCM-wavelength-division-multiplexing (WDM) system, where SCM is used to generate closely spaced channels in the transmitter, while a hyperfine WDM (HWDM) demultiplexer is used at the receiver to optically separate the subcarriers for optical direct detection. A hyperfine optical blocking filter is employed in the transmitter to realize O-SSB modulation with strong carrier suppression. We demonstrate our concept by system experiments which show error-free transmission of four subcarriers over a 50-km single-mode-fiber (SMF) link at 622 Mb/s (OC-12) with channels spaced ~3 GHz. Our detection scheme has several key advantages over the heterodyne detection: no carrier needed (improved optical power efficiency, with the prospect of reduced fiber nonlinearities, as well as improved spectral efficiency), low sensitivity to fiber PMD, and low detection complexity (a low-speed PD matched to the data rate is sufficient, no microwave splitting and mixing). Our work is also the first HWDM experiment employing multiple subcarrier sources at the narrowest WDM channel spacing ~3 GHz.

Fig. 1(a) shows our experimental setup. We use a tunable laser (Agilent 81 680 A) with wavelength at ~1.55 μm as the input to a standard single electrode-drive Mach–Zehnder modulator (MZM) with an electrical 3-dB passband ~30 GHz, biased at the minimum transmission point. The laser source has a linewidth below 0.1 pm (~12.5 MHz) and a stability of ±12.5 MHz. Subcarrier tones at 2.8, 6.0, 8.9, and 11.8 GHz are mixed with four uncorrelated 622-Mb/s pseudorandom bit sequences (2^{23-1}) modulated in amplitude with intensity extinction ratios $\geq$20 dB, combined in a microwave power combiner, and applied to the MZM. The MZM's output spectrum has nine spectra peaks corresponding to a partial suppressed optical carrier and double sidebands (O-DSB) [5]. After being amplified by an erbium-doped fiber amplifier (EDFA) to an average power ~ -10-dBm/subcarrier channel, the MZM's output goes through a hyperfine blocking filter based on a solid virtually imaged phased-array (VIPA) spectral disperser to generate O-SSB with strong carrier suppression [6]. The VIPA, first described in [7], is essentially a side-entrance Fabry–Pérot etalon, which functions as a spectral disperser, with an angular dispersion ($\geq$1 deg/nm) significantly larger than diffraction gratings and a low polarization dependence loss ($\leq$0.1 dB). Fig. 1(b) shows our VIPA-based hyperfine blocking filter setup in a reflective geometry, which in theory should be free of

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The authors are with the School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN 47907-2035 USA (e-mail: sxiao@ecn.purdue.edu; amw@ecn.purdue.edu).

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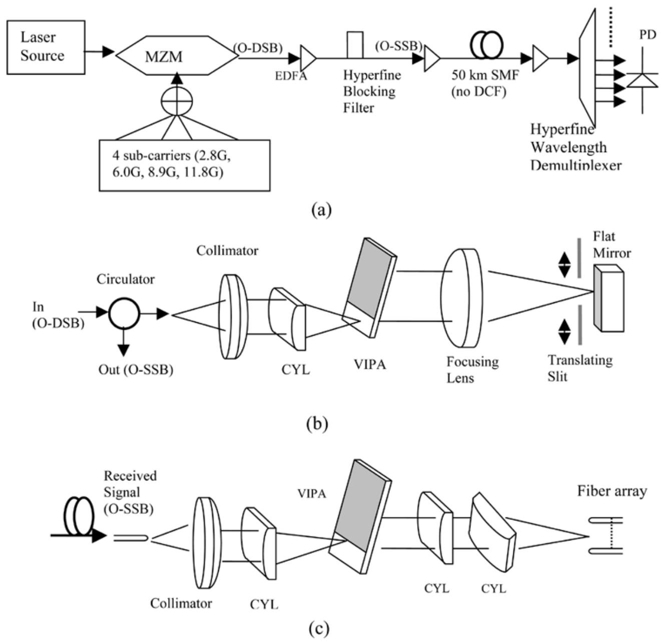


Fig. 1. (a) Experimental setup of four-user ∼3-GHz-spaced SCM using optical direct-detection. (b) Experimental setup of our VIPA-based hyperfine blocking filter. (c) Experimental setup of our eight-channel hyperfine wavelength demultiplexer. CYL: Cylindrical lens.

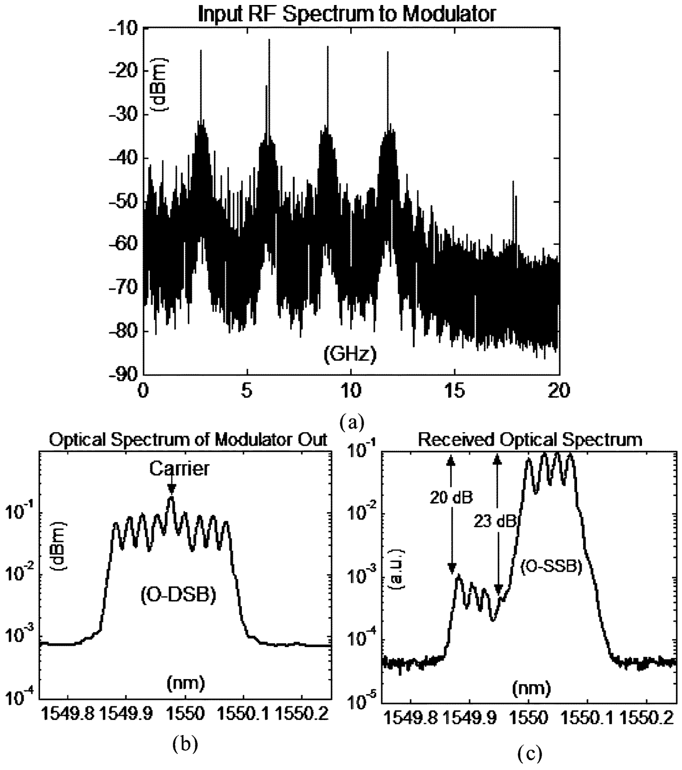
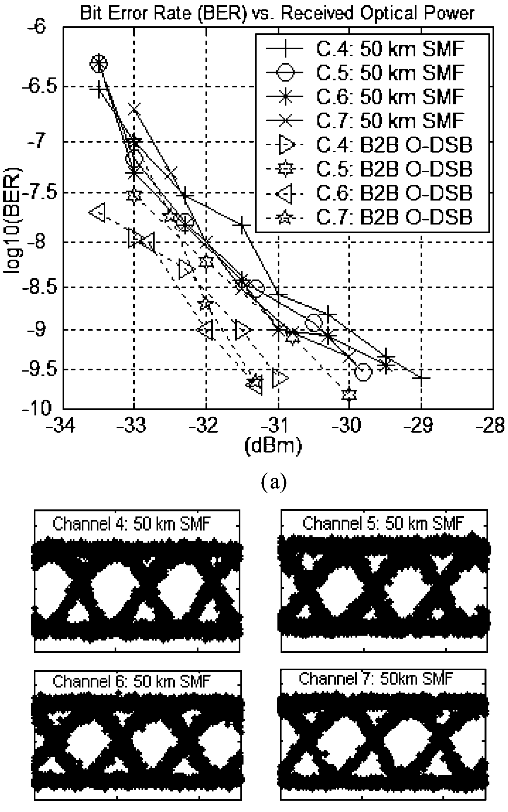


Fig. 2. (a) Input RF spectrum to the MZM, four subcarriers (2.8, 6.0, 8.9, 11.8 GHz) carrying 622 Mb/s ON–OFF keying data. (b) Amplified optical spectrum of the MZM output: O-DSB with partial carrier suppression. (c) Amplified optical spectrum at the 50-km SMF link end: O-SSB with strong carrier suppression.

dispersion. The average total insertion loss of our blocking filter in the reflective geometry is ∼13 dB, which is in the same range reported in [8]. With a perfect implementation, the insertion loss can be theoretically reduced to about 5 dB. The blocking filter has a free spectral range (FSR) of 50 GHz, and the transition of the filter from OFF to ON state occurs in a spectral range ∼3 GHz for a transmission change of ∼25 dB. This indicates a very large rolloff of the transmittance function of ∼1000 dB/nm. The filter can suppress one set of the sidebands as well as the carrier to ≥20 dB below the remaining set of sidebands, resulting in a clean O-SSB spectrum with strong carrier suppression. O-SSB modulation with strong carrier suppression is considered the most efficient modulation format in radio-fiber links since the only power transmitted is the information sideband [9].

After a second EDFA, the launching average power is ∼ −10-dBm/subcarrier channel into the fiber link. After a 50-km SMF link transmission and amplification by an EDFA, the average power is recovered to ∼ −10-dBm/subcarrier channel. Finally, these multiplexed closely spaced subcarrier channels are demultiplexed by a hyperfine wavelength demultiplexer based on another solid VIPA with an FSR of 50 GHz [10]. Fig. 1(c) shows our VIPA-based eight-channel hyperfine wavelength demultiplexer with channels spaced ∼3 GHz, which has a center channel insertion loss ∼12 dB. Theoretically, this insertion loss can be reduced to ∼8 dB for our current design. The adjacent channel isolation is ≥23 dB, and the nonadjacent channel isolation is ≥30 dB. For the four channels (4–7) used here, the spacing is matched to the applied subcarrier frequency spacing. The channel 3-dB bandwidths are ∼0.65 GHz (this is what limits the data rate to 622 Mb/s in our current experiment). The power penalty due to the adjacent channel crosstalk at 622 Mb/s is ≤0.5 dB, and the power penalty due to the single channel optical filtering at 622 Mb/s varies from 1.3 to 1.8 dB (Channels 1–8) [11]. Each channel is detected using an avalanche photodiode (APD) with an electrical 3-dB bandwidth of ∼0.5 GHz matched to the data rate at 622 Mb/s (OC-12).

Fig. 2(a) shows the radio-frequency (RF) spectrum of the input electrical signal to the MZM, with four amplitude modulated subcarriers. Each subcarrier is attenuated to an average RF power ∼ −15 dBm for an approximately linear modulation. Fig. 2(b) shows the amplified optical spectrum of the MZM output, termed as O-DSB with partial carrier suppression. The remaining optical carrier is due to intrinsic modulator limits. The optical signal-to-noise ratio (OSNR) is 21.0 dB for Channel 4 (subcarrier 2.8 GHz), 20.5 dB for Channel 5 (subcarrier 6.0 GHz) and Channel 6 (subcarrier 8.9 GHz), and 20.0 dB for Channel 7 (subcarrier 11.8 GHz) according to the spectra in Fig. 2(b). As O-DSB has two equivalent information bands that result in a low spectral efficiency and a low fiber chromatic dispersion tolerance, the blocking filter is used to suppress one sideband (shorter wavelength part here). In addition, the optical carrier is also strongly suppressed simultaneously (in contrast with the conventional SCM receiver where the optical carrier is transmitted for heterodyne beating detection). The blocking filter also rejects the amplified spontaneous emission (ASE) noise outside of the O-SSB band. Then, the filter output (O-SSB with strong carrier suppression) is launched into the fiber link. Fig. 2(c) shows the amplified received optical spectrum after the 50-km fiber link. The sideband suppression ratio is ≥20 dB, and



(a)

(b)

Fig. 3. (a) BER versus received optical power of APD for four subcarriers' channels using optical direct detection, either B2B directly at the modulator output after amplification or after 50-km fiber transmission. (b) Received eye diagrams of four subcarriers' channels. Channels 4–7 correspond to subcarriers 2.8, 6.0, 8.9, and 11.8 GHz, respectively.

we estimate the optical carrier is suppressed down to ≥ 20 dB lower than the remaining sideband (longer wavelength part). The slight difference (≤ 1 dB) in average optical power/subcarrier channel is attributed to slightly different average RF power/subcarrier driving the MZM as well as the transmission fluctuation (≤ 1 dB) from the blocking filter. As the blocking filter has an FSR of 0.4 nm (50 GHz), the ASE noise level in the O-SSB band can be directly obtained on the spectra response at one FSR away from the O-SSB band. The received OSNR is 18.8 dB for Channel 4 and 19.6 dB for Channels 5–7. Fig. 3(a) shows the bit-error rate (BER) as a function of the input optical power to the APD receiver both back-to-back (B2B) at the amplified MZM output and after the fiber link, and Fig. 3(b) shows received eye diagrams (after the fiber link) of four subcarrier channels. An error-free ($\text{BER} \leq 10^{-9}$) transmission is demonstrated. The maximum power penalty at $\text{BER} = 10^{-9}$ is $\sim$1.5 dB for Channel 4 (subcarrier at 2.8 GHz); the minimum power penalty is $\sim$0.5 dB for Channel 5 (subcarrier at 6.0 GHz). Power penalties may be attributed to effects from the blocking filtering (slight sideband shaping and slight chromatic dispersion) as well as small OSNR degradation due to ASE noises in EDFAs at both the blocking filter output and the receiver. The sensitivity (defined as the corresponding optical power at $\text{BER} = 10^{-9}$) variation among four subcarrier channels at B2B may be attributed to the variation of the single channel filtering as well as intermodulation effects (generating frequency mixing terms). The B2B sensitivities in our case are between -32 and -31 dBm. For a single SCM user, we showed a B2B sensitivity -37 dBm without the optical channel filtering [6], and the B2B sensitivity degradation for multiple SCM users is mainly due to the single optical channel filtering $\sim$1.5 dB as well as the adjacent channel incoherent crosstalk $\leq$0.5 dB, and intermodulation effects resulting in coherent interferences across subcarrier channels.

In summary, we demonstrate error-free four-user $\sim$3-GHz-spaced SCM using optical direct-detection via a hyperfine wavelength demultiplexer in experiments with a 50-km SMF link transmission, where O-SSB modulation with strong carrier suppression is applied for only information band transmission. Compared to the conventional heterodyne beating scheme, our scheme offers higher power efficiency, fundamentally low sensitivity to fiber PMD effects, and reduced receiver complexity (e.g., 500-MHz detector bandwidth requirement as opposed to $>$12 GHz in our current setup). Our work demonstrates the first HWDM system employing multiple subcarrier sources at the narrowest WDM channel spacing $\sim$3 GHz.

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