We propose a novel and simple $2 \times 2$ multiple-input multiple-output (MIMO) optical–wireless integration system, in which optical independent-sideband modulation enabled by an in-phase/quadrature ($I/Q$) modulator, instead of optical polarization multiplexing, is used to assist the simultaneous generation of two wireless millimeter-wave (mm-wave) signals. Software-based digital signal processing is used to generate the driving signal for the $I/Q$ modulator, the output of which is two independent single-sideband optical vector signals located at two sides of a large central optical carrier. Based on our proposed $2 \times 2$ MIMO optical–wireless integration system, we experimentally demonstrate the simultaneous generation and $2 \times 2$ MIMO wireless delivery of two independent 40-GHz quadrature-phase-shift-keying (QPSK) wireless mm-wave signals. Each 40-GHz QPSK wireless mm-wave signal can carry up to 4-Gbaud transmitter data with a bit-error ratio less than the hard-decision forward-error-correction threshold of $3.8 \times 10^{-3}$. © 2016 Optical Society of America

**OCIS codes:** (060.0060) Fiber optics and optical communications; (060.5625) Radio frequency photonics; (060.4080) Modulation.

http://dx.doi.org/10.1364/OL.41.003138

Optical–wireless integration systems integrate large-capacity long-haul fiber-optics communication and high-mobility wireless communication and have the potential to offer large-capacity long-haul wireless transmission links for mobile data communication [1–18]. In numerous optical–wireless integration systems reported recently by the research community, a wireless multiple-input multiple-output (MIMO) technique is employed to increase wireless transmission capacity, in order to match ultralarge fiber-optics transmission capacity [8–14]. However, in order to assist the simultaneous generation of multiple wireless millimeter-wave (mm-wave) signals used for wireless MIMO delivery, the existing MIMO optical–wireless integration systems typically require the employment of both optical polarization multiplexing and optical polarization diversity [8–14], which significantly increases the complexity of the system architecture. Lin et al. proposed a $2 \times 2$ MIMO orthogonal-frequency-division-multiplexing optical–wireless integration system employing optical subcarrier multiplexing enabled by an in-phase/quadrature ($I/Q$) modulator, which avoids both optical polarization multiplexing and optical polarization diversity [15]. However, in this system, the driving signals for the $I/Q$ modulator are generated in the electrical domain, which requires a very complicated transmitter electrical circuit; moreover, an electrical carrier is needed to generate the optical carrier, which further complicates the transmitter electrical circuit.

In this Letter, we propose a novel and simple $2 \times 2$ MIMO optical–wireless integration system adopting optical independent-sideband (ISB) modulation enabled by an $I/Q$ modulator. Software-based digital signal processing (DSP) is used to generate the driving signal for the $I/Q$ modulator in the digital domain. The output of the $I/Q$ modulator is two independent single-sideband (SSB) optical vector signals located at two sides of a large central optical carrier. Compared to previously reported MIMO optical–wireless integration systems [8–14], both optical polarization multiplexing and optical polarization diversity are avoided, which significantly simplifies the system architecture and increases the system stability. Compared to the MIMO optical–wireless integration system proposed by Lin et al. [15], both the complicated transmitter electrical circuit and the electrical carrier are avoided, which also significantly simplifies the system architecture and increases the system stability. Based on our proposed $2 \times 2$ MIMO optical–wireless integration system, we experimentally demonstrate the simultaneous generation and $2 \times 2$ MIMO wireless delivery of two independent 40-GHz quadrature-phase-shift-keying (QPSK) wireless mm-wave signals. Each 40-GHz QPSK wireless mm-wave signal can carry up to 4-Gbaud transmitter data with a bit-error ratio (BER) less than the hard-decision forward-error-correction (HD-FEC) threshold of $3.8 \times 10^{-3}$.

Figure 1 shows the schematic diagram of our proposed $2 \times 2$ MIMO optical–wireless integration system, adopting optical
The generated optical ISB signal is then sent into an optical filter (OF) with two optical outputs. The OF can be an optical interleaver (IL) or a programmable wavelength selective switch. One output of the OF is the central optical carrier at frequency $f_c$ and the optical USB at frequency $f_{s1} + f_c$, and it is upconverted by a single-ended photodiode (PD) to an electrical vector mm-wave signal at frequency $f_{s1}$ carrying $s1$. The other output of the OF is the central optical carrier at frequency $f_c$ and the optical LSB at frequency $f_{s2} - f_c$, and it is upconverted by another single-ended PD to an electrical vector mm-wave signal at frequency $f_{s2}$ carrying $s2$. The aforementioned two simultaneously generated electrical vector mm-wave signals are delivered by a $2 \times 2$ MIMO wireless link including two pairs of antennas. Each transmitter antenna and its corresponding receiver antenna have a high directionality, and almost no wireless interference exists in the $2 \times 2$ MIMO wireless link. At the wireless receiver end, two analog-to-digital converters (ADCs) are required for the simultaneous processing of the received two electrical vector mm-wave signals. Analog downconversion may be first implemented before ADC processing for the mm-wave signals with relatively high carrier frequency [8]. The subsequent DSP includes downconversion, constant-modulus algorithm (CMA) equalization or cascaded multi- $\mu$- algorithm (CMMA) equalization, carrier recovery, and BER calculation [23]. It is worth noting that imperfect optical ISB modulation by the $I/Q$ modulator and imperfect optical filtering by the optical IL may lead to interference between the two ISBs [21], which, however, can be effectively eliminated by DSP-based receiver CMA/CMMA equalization [10].

Figure 2 gives the experimental setup of our proposed $2 \times 2$ MIMO optical–wireless integration system adopting optical ISB modulation enabled by an $I/Q$ modulator. At the transmitter end, the $I$ and $Q$ inputs for the 80-GSa/s DAC with 16-GHz, 3-dB electrical bandwidth are generated by MATLAB programming. Here, the PRBS length is $2^{29}$. Both $s1$ and $s2$ adopt QPSK modulation and also have identical baud rates at 1, 2, 4, or 8 Gbaud. $f_{s1}$ and $f_{s2}$ are both equal to 40 GHz. The amplified $I$ and $Q$ outputs of the 80-GSa/s DAC are used to drive an $I/Q$ modulator with 32-GHz, 3-dB optical bandwidth. The optical input of the $I/Q$ modulator is a CW lightwave at 1548.706 nm generated from an external cavity laser with $<100$ kHz linewidth and 13-dBm output power. The output optical power of the $I/Q$ modulator is $-22$ dBm. Figure 2(a) gives the measured output optical spectrum of the $I/Q$ modulator, showing two independent QPSK sidebands spaced by 40 GHz from the central optical carrier. After a boost by an erbium-doped fiber amplifier (EDFA), the generated optical ISB signal is transmitted over 20-km SMF-28 in the absence of optical dispersion compensation and then sent into a 50/100-GHz optical IL. Figure 2(b) gives the measured output optical spectrum of the EDFA. Figures 2(c) and 2(d) give the two measured output optical spectra of the optical IL, showing two independent 40-GHz optical mm-wave signals are generated by suppressing USB or LSB.

As we know, the $I/Q$ modulator is actually composed of two intensity modulators (IMs) and one phase modulator (PM), and thus have three independent DC biases [19]. In our experiment, we adjust the three DC biases of the $I/Q$ modulator by two steps. In the first step, we adjust the three DC biases to ensure that the two IMs have a minimum...
output optical power and the PM has a \( \pi/2 \) phase shift. Then, in the second step, we appropriately adjust the DC biases of the two IMs while fixing the DC bias of the PM to ensure that in the output of the I/Q modulator the power of the central optical carrier is 3 dB larger than that of the two optical SSBs, just as shown in Fig. 2(a).

Each 40-GHz optical mm-wave signal is upconverted by a single-ended PD to a 40-GHz QPSK electrical mm-wave signal. Each PD operates within the frequency range from 33 to 50 GHz and has a 60-GHz optical bandwidth. It is worth noting that a variable optical attenuator is added before the optical IL to adjust the input power into each PD for BER measurement. After boost by two parallel narrowband 40-GHz electrical amplifiers, the two 40-GHz electrical mm-wave signals are delivered by a 1-m \( 2 \times 2 \) MIMO wireless link, which adopts two pairs of Q-band horn antennas (HAs), each with a 25-dBi gain. Two transmitter (receiver) HAs have a 0.03-m separation. The two received 40-GHz wireless mm-wave signals after 1-m wireless delivery are first amplified by two parallel low-noise amplifiers and then sent into two ADC channels of a 160-GSa/s digital storage oscilloscope (OSC) with 65-GHz 3-dB electrical bandwidth for the subsequent DSP. Here, CMA equalization is used to eliminate the interference between two independent sidebands. Figures 2(a)–2(d) are all measured at 0.02-nm resolution and 2-Gbaud per sideband.

In the scenario of no fiber transmission and no wireless delivery, Fig. 3 gives the measured BER versus input power into each PD for two independent 40-GHz wireless mm-wave signals both at 1, 2, 4, and 8 Gbaud, respectively. We can see that, at the same baud rate, two independent 40-GHz wireless mm-wave signals (corresponding to LSB and USB, respectively) have quite similar BER performance. The BER can reach the HD-FEC threshold of \( 3.8 \times 10^{-3} \) for all the 1-, 2-, and 4-Gbaud cases, while an error floor exists at the BER of \( 1 \times 10^{-3} \) for the 8-Gbaud case. Moreover, at the HD-FEC threshold of \( 3.8 \times 10^{-3} \), compared to the 1-Gbaud case, there exist 1.3- and 9.3-dB power penalties for the 2- and 4-Gbaud cases, respectively. The degradation of BER performance with the increase of the baud rate is mainly due to the limited DAC bandwidth of only 16 GHz, which is particularly insufficient for the generation of 40-GHz sideband carrying 8-Gbaud QPSK data. It is worth noting that the adopted CMA-tap numbers are 9, 17, 29, and 41 for the 1-, 2-, 4-, and 8-Gbaud cases, respectively. The reason more CMA taps are required at higher baud rates is that the increase of baud rate exacerbates the interference between the two independent sidebands, which thus requires CMA equalization with more taps to eliminate.

In the scenario of no fiber transmission and no wireless delivery, Fig. 4 gives the measured BER versus CMA-tap number for 1-Gbaud 40-GHz wireless mm-wave signal corresponding to USB. The input power into each PD is fixed at \( -10.5 \) dBm. We can see that the BER varies significantly when different CMA-tap number is adopted, and the optimum CMA-tap number is 17. We also experimentally verified that the counter-
part case corresponding to LSB has a quite similar performance. The optimal additional CMA-tap number can be calculated as follows [10]:

\[ \Delta n = 2nlb/c, \tag{1} \]

where \( n \) is the medium index, \( l \) is the path difference between the two independent signals, \( c \) is the optical speed in vacuum, and \( b \) is the baud rate. For example, in the scenario of no fiber transmission and no wireless delivery discussed in Fig. 3, we can conclude from Eq. (1) that, compared to the 1-Gbaud case with 9 CMA taps, if the optimal additional CMA-tap number is 8 for the 2-Gbaud case \((9 + 8 = 17)\), the optimal additional CMA-tap numbers are about 16 and 32 for the 4-Gbaud case \((9 + 16 = 25)\) and the 8-Gbaud case \((9 + 32 = 41)\), respectively. These calculated theoretical values of 25 and 41 are very close to our practically adopted values in Fig. 3 (29 for 4 Gbaud and 41 for 8 Gbaud).

Figure 5 gives the BER versus the input power into each PD for 1-Gbaud 40-GHz signal corresponding to USB in three different scenarios: neither fiber transmission nor wireless delivery (Scenario 1), 1-m wireless delivery but no fiber transmission (Scenario 2), and both 20-km SMF-28 transmission and 1-m wireless delivery (Scenario 3). Both 20-km SMF-28 transmission and 1-m wireless delivery almost cause no power penalty, and the BER can reach \(3.8 \times 10^{-3}\). Note that the adopted CMA-tap number is 9, 11, and 13 for Scenarios 1–3, respectively. The reason Scenario 2 requires two more CMA taps and Scenario 3 requires 4 more CMA taps is that both 20-km SMF-28 transmission and 1-m wireless delivery contribute to the exacerbation of the walk-off effect of the mm-wave signal. We also experimentally verified that the counterpart case corresponding to LSB has a quite similar performance. We measured the received signal spectra and recovered constellations for two independent 1-Gbaud 40-GHz signals after 20-km SMF-28 transmission and 1-m wireless delivery at -11-dBm input power into each PD. Insets (a) and (b) in Fig. 5, respectively, give the received signal spectra and recovered constellations corresponding to LSB, while insets (c) and (d) in Fig. 5 give those corresponding to USB. The adopted CMA-tap number is 13. The BERs for two signals are all below \(1 \times 10^{-6}\).

As a conclusion, we propose a novel and simple \(2 \times 2\) MIMO optical–wireless integration system, in which optical ISB modulation enabled by an I/Q modulator, instead of optical polarization multiplexing, is used to assist the simultaneous generation of two wireless mm-wave signals. We experimentally demonstrate, based on our proposed system, the simultaneous generation and \(2 \times 2\) MIMO wireless delivery of two independent 40-GHz QPSK wireless mm-wave signals, each of which can carry up to 4 Gbaud transmitter data with a BER less than \(3.8 \times 10^{-3}\). We can anticipate, based on our proposed system, we can further realize the simultaneous generation and \(2 \times 2\) MIMO wireless delivery of two independent wireless mm-wave signals with different modulation formats, baud rates, and carrier frequencies.

**Funding.** National Natural Science Foundation of China (NSFC) (61325002, 61250018, 61527801); National High-tech R&D Program (863 Program) of China (2015AA016904); Key Program of Shanghai Science and Technology Association (13JC1400700); Ph.D. Programs Foundation of Ministry of Education of China (20120071110032).

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