Full-duplex wireless-over-fibre transmission incorporating a CWDM ring architecture with remote millimetre-wave LO delivery using a bi-directional SOA

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Abstract: We demonstrate the first full-duplex wireless-over-fibre transmission between a central station and a CWDM ring architecture with remote 40 GHz LO delivery using a bi-directional semiconductor optical amplifier.

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1. Introduction
Wireless-over-fibre is an attractive technology for future broadband wireless access systems operating in the millimetre-wave frequency range. In previously reported wireless-over-fibre systems separate uni-directional erbium doped fibre amplifiers (EDFAs) were used to provide the necessary gain for the downlink and uplink [1,2]. In this paper, we report the first demonstration of the use of bi-directional semiconductor optical amplifiers (SOAs) to provide gain for both downlink and uplink optical signals simultaneously, together with the first experimental results for a coarse wavelength division multiplex (CWDM) ring architecture which allows distribution of a centrally generated 40 GHz local oscillator (LO) signal and the connection of multiple base stations in a wireless-over-fibre network.

The use of bi-directional SOAs in place of uni-directional EDFAs, together with the use of CWDM and optical distribution of the millimetre-wave local oscillator signal allows substantial reduction in overall systems complexity and cost, as will be necessary for the widespread adoption of millimetre-wave wireless access systems. It also increases utilisation of the deployed fibre, an economic advantage where leased fibre has to be used.

2. System Overview
The system comprises a 12.8 km standard single mode fibre (SMF) backbone link with a 2.2 km fibre ring for distribution to the wireless base stations. 3.5 MSymb/s wireless data signals to and from the base stations are distributed at intermediate frequencies (IFs) in the 2.40 GHz to 2.50 GHz band to overcome fibre dispersion using directly modulated uncooled distributed feedback (DFB) lasers. The laser emission wavelengths are selected on a 20 nm pitch CWDM grid to route signals to/from the required base station. The LO source at 40 GHz is generated optically at the central station and is delivered to multiple remote base stations. The delivery of the LO signal is also tolerant to fibre dispersion since it is generated in single sideband form. The common LO signal is used at each base station to up-convert down-link IF signals and down-convert received up-link signals.

3. Optically Generated 40 GHz Local Oscillator Source
The 40 GHz LO source is optically generated at the central station by injection locking two slave DFB lasers to two sidebands of an externally modulated master tunable laser. Fig. 1 illustrates the experimental arrangement of this 40 GHz LO source.

In Fig. 1 the Mach-Zehnder (MZ) modulator externally modulates the output of the CW tunable master laser source whose centre wavelength is set at 1543.6 nm (λ₀) with 8.1 dBm output power. Because the MZ modulator is biased at 7.3V (V₀), the unmodulated optical transmission is minimum. When the MZ is driven by a 20 GHz microwave signal generator, its optical output then contains mainly two modulation sidebands located at ± 20 GHz offset from the suppressed 1543.6 nm line. The two main sidebands are therefore 40 GHz apart and effectively the MZ is functioning as a frequency doubler. Slave DFB 1 is injection locked by one sideband and Slave DFB 2 by the other. The injection locked outputs of the two slave lasers are then combined in a 50%/50% coupler forming a 40 GHz heterodyne beat signal. Previously Braun et al. reported generation of a 64 GHz signal by optical injection
locking two slave DFB lasers to the −10th and +10th modulation sidebands of a master DFB laser which was directly and heavily modulated at 3.2 GHz with +23.4 dBm input [3].

The advantages of heterodyning the two injection locked slave DFB lasers instead of simply taking the frequency doubled output directly from the MZ modulator are the 15 dB increase in the optical output power level and the further suppression of the tunable laser source centre wavelength at 1543.6 nm. Since the two modulation sidebands are each offset by 20 GHz from 1543.6 nm, insufficient suppression of this centre wavelength would result in the generation of an unwanted 20 GHz signal in the detected RF spectrum of the LO source output. Fig. 2 shows the detected RF spectrum of this 40 GHz heterodyne LO source in a full 50 GHz span.

4. Wireless-over-fibre transmission experiment and results

Fig. 3 shows the complete experimental arrangement of the wireless-over-fibre transmission system. Full-duplex transmission occurs between the Central Station and Base Station 1. Base Station 1 is connected via optical add-drop multiplexer (OADM) 1 to a 2.2 km single-mode fibre (SMF) ring. The fibre ring in turn is connected to the Central Station via a bi-directional SOA and a 12.8 km back-bone SMF. The OADMs used are constructed using low cost CWDM filters and are employed for routing different wavelengths to their intended remote base stations. Measured optical and detected electrical spectra at various points in the transmission experimental arrangement are also shown in Fig. 3.
In the down-link direction, Laser 1, operating at 1512.3 nm wavelength ($\lambda_1$), at the Central Station is directly modulated with 3.5 MSymb/s QPSK data at 2.40 GHz carrier frequency (Channel 1) provided by a Vector Signal Generator (VSG). $\lambda_1$ is multiplexed with the output of the optically generated 40 GHz LO source whose two sidebands are centred around wavelength $\lambda_0$. Both $\lambda_0$ and $\lambda_1$ are then transported to the fibre ring via the 12.8 km SMF and the bi-directional SOA. At OADM 1, the $\lambda_1$ signal, carrying the QPSK data, is dropped and delivered to Base Station 1. Around 50 % of the $\lambda_0$ power carrying the LO is also dropped and delivered to Base Station 1 by OADM 1 whilst the remaining 50 % is allowed to proceed to OADM 2 and to be used for further frequency conversions elsewhere. After photo-detection, the QPSK data is up-converted to 40 GHz ± 2.4 GHz using the remotely delivered 40 GHz LO source. In order to demodulate the downlink signal and to assess the transmission performance, the up-converted signal is then down-converted back to 2.4 GHz using an independent 40 GHz LO before the QPSK data is detected by a Vector Signal Analyzer (VSA).

In the uplink direction, Laser 2 of 1532.7 nm wavelength ($\lambda_2$) at Base Station 1 is directly modulated with 3.5 MSymb/s QPSK data at 2.41 GHz (Channel 2) provided by another VSG. $\lambda_2$ now carrying the uplink QPSK signal is first sent round the fibre ring before going through the SOA and the 12.8 km SMF, and finally arriving at the Central Station. A 1 nm optical bandpass filter is used to select $\lambda_2$ which is then photo-detected and subsequently demodulated by the VSA. As can be seen in Figure 3, the detected electrical spectrum of $\lambda_2$ contains both Channel 1 and Channel 2 signals even though $\lambda_2$ is not present after the optical bandpass filtering. The transfer of the Channel 1 signal onto $\lambda_2$ can be attributed to the cross-gain modulation characteristic of the SOA where both $\lambda_1$ and $\lambda_2$ are simultaneously present. Since the downlink and uplink signals use different subcarrier frequencies (2.40 GHz and 2.41 GHz, respectively), Channel 2 can be easily selected for demodulation by simple electrical filtering.

Fig. 4(a) shows the constellation, electrical spectrum, eye-diagram and signal statistics for the downlink Channel 1 QPSK signal measured and demodulated by the VSA while Fig. 4(b) shows the corresponding results for the uplink Channel 2 signal. Successful full-duplex transmission has been achieved as evident from the clear and well-defined constellations and eye-diagrams as well as low 10.5% and 7.8 % error vector magnitude (EVM) values for the downlink and uplink directions, respectively.

![Fig. 4. Demodulated 3.5 MSymb/s QPSK data for the downlink and the uplink. The four quadrants show the constellation diagram, electrical spectrum, eye diagram, and signal statistics.](a) Downlink  (b) Uplink)

5. Conclusions
A full-duplex 3.5 MSymb/s QPSK wireless data over 12.8 km fibre transmission with a bi-directional SOA incorporating a 2.2 km CWDM fibre ring architecture has been experimentally demonstrated for the first time. Successful transmission has been achieved as evident in the clear and well-defined constellations and eye-diagrams as well as low 10.5% and 7.8 % EVM values for the downlink and uplink directions, respectively. The cost savings obtained from the use of CWDM and bi-directional SOA technology, together with the improved fibre utilisation resulting will make such solutions more attractive for future millimetre-wave access systems.

6. References