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Simultaneous Generation and Routing of Millimetre-Wave Signals exploiting Optical Frequency Multiplication

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Abstract *Exploiting an integrated micro-ring resonator, the simultaneous generation and routing of millimetre-wave signals by optical frequency multiplication is demonstrated for in-building networks. Error Vector Magnitude < 5% is achieved for up to 120Mb/s 64-QAM at 39.6 GHz carrier frequency.*

Introduction

With increasing requirement for high-capacity in-building networks, radio-over-fibre (RoF) distribution antenna systems are gaining attraction due to the potential to extend radio coverage by the large bandwidth and transparency to signal formats available in fibre. To exploit this bandwidth, millimetre-wave frequencies (30-70GHz) are seen as a viable broadband wireless access technology for in-building RoF systems due to low spectrum congestion, low interference and potential for high data rates. In addition, the inability of millimetre-wave (mm-wave) to penetrate walls is ideal for creating picocells enabling high-capacity, secure and robust transmission within a particular room. However, difficulties in the generation, transmission and routing of mm-wave signals has limited its adoption for this application.

Currently, most methods of mm-wave generation are based on three main approaches: direct-modulation, external modulation, and remote heterodyning. Firstly, the bandwidth limitation of available direct-modulation lasers proves unsuitable for mm-wave applications and the use of external modulation requires a high-frequency signal to drive expensive optical modulators[1]. Another approach is to employ a local oscillator (LO) mixed with the intermediate frequency radio signals to up-convert to mm-wave signals requiring high-frequency oscillators and mixers[2]. Other methods based on optical heterodyning techniques exploit two optical sources operating at different wavelengths to beat at a photo-detector generating mm-wave signals[3]. These methods encounter issues including non-linear distortions when modulating and distributing mm-wave signals. Moreover, expensive high-frequency components and the use of several laser sources in the latter leads to higher complexity and cost.

Therefore, for low-complexity in-building network applications, optical frequency multiplication (OFM) allows mm-wave signals to be generated using low frequency components[4]. Various in-building network architectures have been studied showing that deploying mm-wave within a fibre-based bus architecture is the most cost-effective for RoF in-building networks[5]. Hence in this paper, mm-wave signals are generated in a bus architecture by using OFM and an add-drop multiplexer (ADM) based on an integrated passive micro-ring resonator at the antenna site. At the same time, the radio signals can be routed to individual rooms. By exploiting the highly selective filter characteristics of micrometer-radius micro-ring resonators, extremely small-area devices can be integrated with the antenna on the same compact optical chip, which leads to reduced power consumption and costs for wide-scale deployments.

We demonstrate the suitability for greenfield in-building installations using single-mode fibre by a proof-of-concept experiment. Successful optical up-conversion of 3.6 GHz radio signal encoded with 64-QAM data at up to 20MS/s (120Mb/s) to a 39.6 GHz mm-wave frequency is achieved. After routing to the remote antenna, the detected signal demonstrates an error vector magnitude (EVM) of only 4.9% (-26.18dB) at 39.6 GHz.

Principle of Generation of Millimetre-Wave Signals using Micro-Ring Resonators

The envisaged network scenario is shown in Fig. 1. The transparent residential gateway (RG) terminating the access network, routes the radio data signals via the fibre infrastructure to the different rooms. At the RG, the wavelengths bearing the radio signals are phase-modulated by a sweep signal and sent to the rooms. At each room, an integrated micro-ring resonator near the antenna drops a specific wavelength to which the micro-ring is tuned. Simultaneously the periodic filtering function of the rings enables the PM-IM conversion necessary in the OFM method to generate the mm-wave RF carriers at

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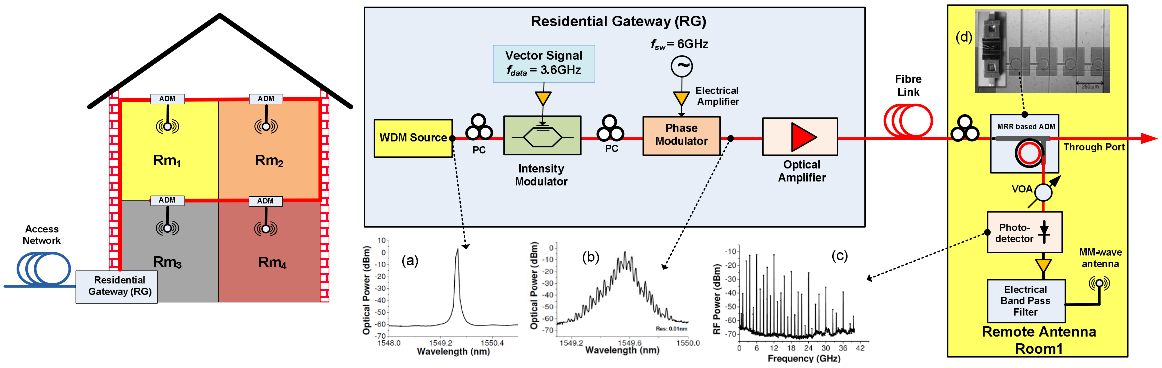


Fig. 1: In-Building bus network architecture with micro-ring resonator assisted routing and mm-wave generation at the remote antenna (Inset: (a)-(c) Optical spectra (d) Micro-ring resonator device).

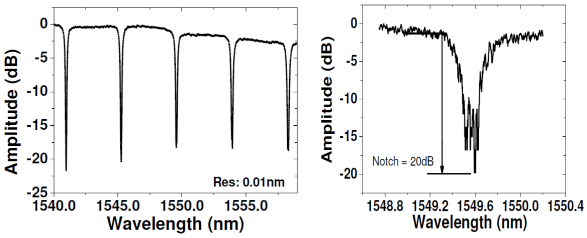


Fig. 2: (a): Transparent Response of the Micro-Ring Resonator **(b):** A magnification of the notch at 1549.6nm

multiples of the sweep signal[4]. The radio signals are hence up-converted and reproduced as double side-band signals at each harmonic. By employing an electrical band-pass filter (BPF) for selecting the appropriate harmonic, the mm-wave radio signal is extracted for air-transmission.

Experimental Procedure and Results

The experimental setup employed to demonstrate the micro-ring based routing and mm-wave generation system is shown in Fig. 1. The continuous wave (cw) light at a wavelength destined for a particular room (Rm_1 = 1549.6nm) is intensity-modulated by 64QAM radio signals at low frequency subcarrier generated by a vector signal generator (VSG) at 3.6 GHz. The signal is then phase-modulated (PM) with a sweep RF signal at f_{sw} =6 GHz. The signal is then input via polarisation controllers (PC) to minimise the polarisation-dependent loss (5dB) of the micro-ring resonator. The loss between input and drop ports of 19dB (consisting of coupling and waveguide loss) is compensated by the pre-amplifier before the micro-ring resonator.

The pigtailed vertically-coupled micro-ring resonator (MRR) was fabricated[*] using Silicon Nitride (Si_3N_4/SiO_2) materials system (high contrast material system, $\Delta n \approx 0.55$)[6] where the highly selective MRR-based filters allow for the fabrication of complex devices on a small footprint. It should be noted, however, that this device could also be realised readily in silicon waveguides using the vertically-stacked double silicon-on-insulator photonic system. The transfer function of the pass-through port is shown in Fig. 2a indicating the free spectral range of 4.4nm.

Corresponding to $room_1$, the filter notch at 1549.6nm is shown in Fig. 2b and indicates an amplitude of 20 dB. At $room_1$, the MRR drops this wavelength. The signal is then detected by a 70 GHz PIN photo-detector (U^2T XPDV3120R) with a flat-response sensitivity of 0.6 A/W and is analysed using an electrical spectrum analyser.

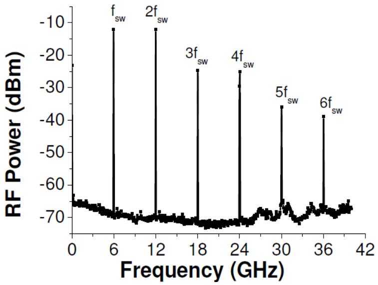
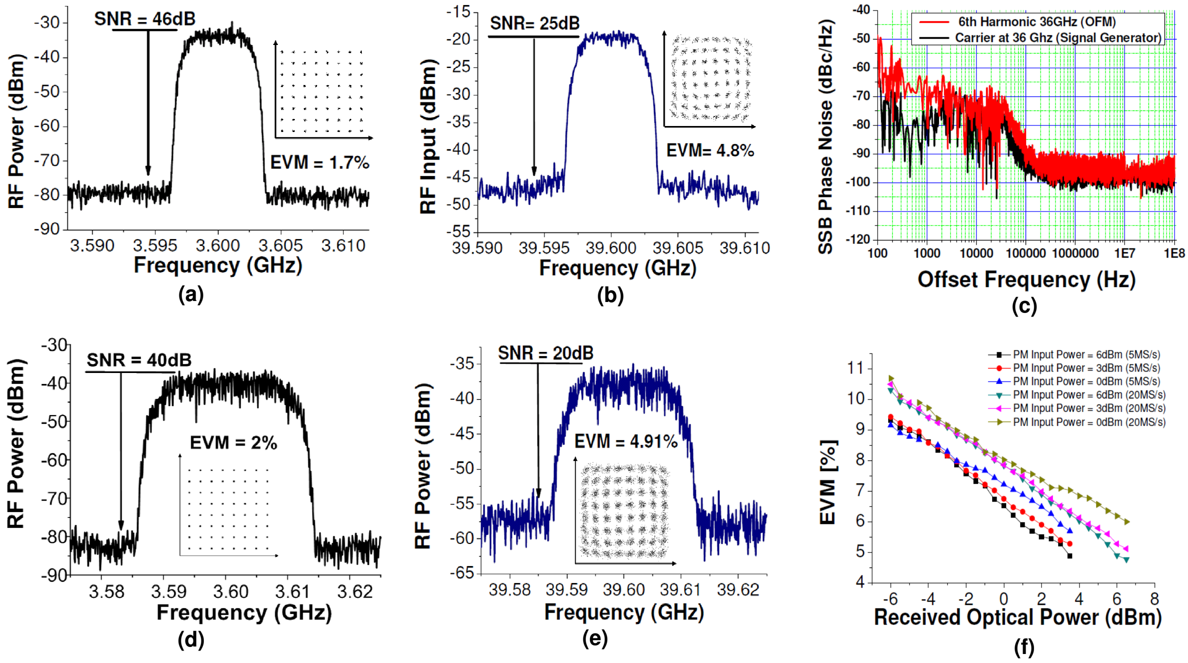


Fig. 3: Harmonics generated by OFM after photodetection with f_{sw}= 6 GHz

Fig. 3 shows the electrical spectrum of the resulting harmonics generated at the photodetector which appear at multiples of the f_{sw}. Note that in this experiment, the RF power injected into the phase modulator is varied to optimise the amplitude of the 6th harmonic at 36 GHz. The modulation index β was calculated to be 2.5.

By single-sideband (SSB) phase noise measurements of the 6th harmonic, a comparison against a reference high frequency carrier generated at 36 GHz from a synthesiser (Agilent E83505L) is obtained. From Fig. 4(c), the phase noise of the OFM-generated harmonic at 36 GHz is shown to be from -50 to -70 dBc/Hz in the 100Hz-1kHz region reducing to -104 dBc/Hz. The phase noise is shown to be of comparable quality as the synthesized source and hence robust for up-conversion. As data is input, the up-converted radio signals bearing data are generated double-sideband of the up-converted harmonics upto 39.6 GHz ($f_{RF} = n.f_{sw} \pm f_{data}$ where n corresponds to n^{th} harmonic, f_{sw} = 6



(a) (b) (c) (d) (e) (f)

Fig. 4: **(a):** RF spectra of input 5MS/s 64-QAM signal at 3.6 GHz (inset: IQ constellation) **(b):** Received 5MS/s 64-QAM signal after up-conversion at 39.6 GHz **(c):** Phase noise performance of 6^{th} Harmonic.
(d): RF spectra of input 20MS/s 64-QAM **(e):** RF Spectra of up-converted 20MS/s 64-QAM at 39.6 GHz
(f): EVM performance of up-converted data.

GHz and f_{data}= 3.6 GHz). Fig. 1 (inset c) shows the spectrum of the up-converted data which appears at each harmonic.

The electrical input data of Fig. 4(a) and 4(d) from the VSG is shown to have a back-to-back EVM of 1.7% and 2.0% for 5MS/s and 20MS/s respectively. After up-conversion, the recovered data is shown to have an EVM of 4.8% (-26.37dB) and 4.91%(-26.18) for 5MS/s and 20MS/s, a penalty of 3.1% and 2.9% respectively. The inset in-phase and quadrature (IQ) constellation diagrams in Fig. 4(b) and 4(e) for 5MS/s and 20MS/s 64-QAM signals at 39.6 GHz shows clear separation between points. In Fig. 4(f), further measurements shows the EVM performance with respect to received optical power for different PM input powers. The EVM performance is similar for PM input powers of 3 and 6dBm, achieving below 5%. However, when the PM input power is reduced to 0dBm, the EVM values are higher saturating at 5.9%.

The main contribution to the penalty can be seen in Fig. 4(b) and (e) where the reduced signal to noise ratio (SNR) penalty is approximately 20dB between the input and up-converted RF signals. The SNR penalty can be attributed mainly to the ASE noise from the optical amplifier used to compensate the loss of the integrated micro-ring resonator. Despite the SNR penalty, the performance of the up-converted data at 39.6 GHz for both 5MS/s and 20MS/s is shown to meet the EVM requirement of 5.6% for the 64 QAM (¾ code rate) IEEE 802.11a/g wireless standards.

Conclusions

The successful generation and routing of mm-wave signals is presented using a micro-ring resonator integrated at the antenna site for in-building networks. Optical up-conversion of radio signals from low-frequency to the mm-wave frequency region is achieved. At the receiver, the data-bearing wavelength channel exhibited an EVM performance of 4.8% and 4.91% for 5MS/s (30Mb/s) and 20MS/s (120Mb/s) 64QAM data at 39.6 GHz, respectively, meeting the requirements for IEEE802.11a/g. By exploiting silicon-on-insulator materials, the viability and low-complexity of this system can be further enhanced by the compact integration of lower loss micro-rings, the receiver and the antenna on a low-loss compact chip.

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