Fig. 5 shows the case of an input signal with a lower crosstalk level (−18 dB). In this case the original signal exhibits low error rates but since $Q = 5.5$, it does not reach a BER of 10^{-9} level. The converted signals have very large Q-factor values, as seen in the detected eye diagrams and reach error-free operation.

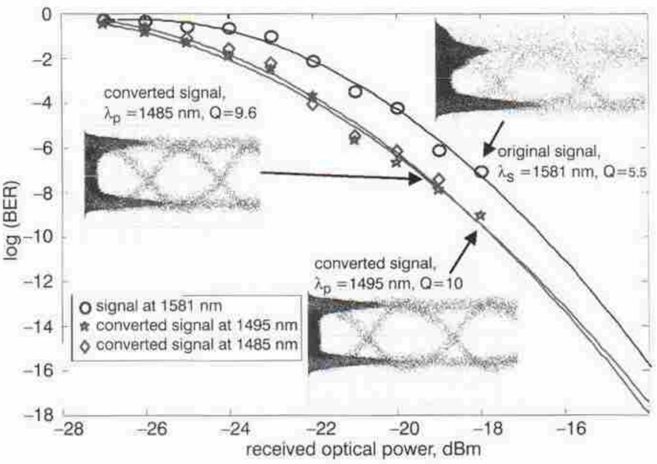

Fig. 5 *BER curves and detected eye diagrams for 10 Gbit/s input signal with moderate noise level and two converted wavelengths*

At 1500 and 1490 nm the probe is close to the Stokes shift frequency and exhibits a small walk-off (<20 ps) yielding an extinction ratio (ER) larger than 12 dB. At 1470 nm, the walk-off increases to ~110 ps while at the same time the Raman efficiency is reduced so that the converted signal presents distortions and the observed ER decreases to 9.5 dB.

The performance of the wavelength converter was examined by BER measurements for a 10 Gbit/s signal and with two levels of crosstalk. Fig. 4 shows the BER curves for the original signal with a large level of crosstalk (−13 dB) and for three converted probes at 1495, 1485 and 1480 nm. Also shown are detected eye diagrams for the original and one of the converted signals. The noisy input signal exhibits a clear BER floor but the converted signals enable error-free operation. The BER curve at 1480 nm is extrapolated beyond −20 dBm because of the limited available probe power. The superior BER performance is consistent with the enhanced Q-factor see

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Photonically assisted generation of continuous arbitrary millimetre electromagnetic waveforms

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A novel optical-to-electrical technique for the generation of continuous periodic arbitrarily shaped millimetre-wave electromagnetic waveforms at centre frequencies of 50 GHz is demonstrated. Tailored optical pulse sequences from a novel direct space-to-time pulse shaper driving a high-speed photodiode enable generation of arbitrary phase- and frequency-modulated waveforms on a cycle-by-cycle basis.

Introduction: Arbitrary optical waveform generation via Fourier transform (FT) pulse shaping is now a widely accepted technique finding application in a variety of areas from optical communications to coherent quantum control [1]. Technologies for the generation of arbitrary electrical waveforms in the microwave and millimetre-wave frequency band are extremely limited however, with commercial instruments simulating real world signals up to only ~2 GHz. Simple methods of generating strongly modulated broadband waveforms at centre frequencies in the multiple tens of GHz could find applications in radio-frequency communications, pulsed radar, and electronic counter-measures. Use of tailored, arbitrary optical pulse sequences to drive a high-speed optical-to-electrical (O/E) converter provides a straightforward method of generating these waveforms and could dramatically enhance the state-of-the-art in microwave and millimetre-wave arbitrary waveform generation. Generation of a phase-modulated waveform in the ~6 GHz range has been demonstrated using a wavelength division multiplexing technique combined with a series of optical delay lines [2]. FT pulse shaping has also been utilised in generating freely propagating, phase-, frequency-, and amplitude-modulated THz waveforms [3]. We recently demonstrated generation of burst waveforms, in the 30 to 50 GHz range, using a 40 MHz passively modelocked fibre laser and a direct space-to-time pulse shaping technique [4]. The phase- and frequency-modulated millimetre-wave signals contained ~6 electromagnetic cycles at centre frequencies up to ~50 GHz, filling a time aperture of ≤140 ps and repeating every 25 ns. In this Letter we present the first demonstration to our knowledge of continuous periodic arbitrary millimetre waveform generation. We replace the passively modelocked source laser with an actively modelocked fibre laser with a 10 GHz repetition rate. As a result we demonstrate for the first time to our knowledge generation of continuous, periodic arbitrary millimetre-wave electromagnetic waveforms. With centre frequencies of ~50 GHz, these continuous waveforms effectively fill the frequency range between previous results [2–4].

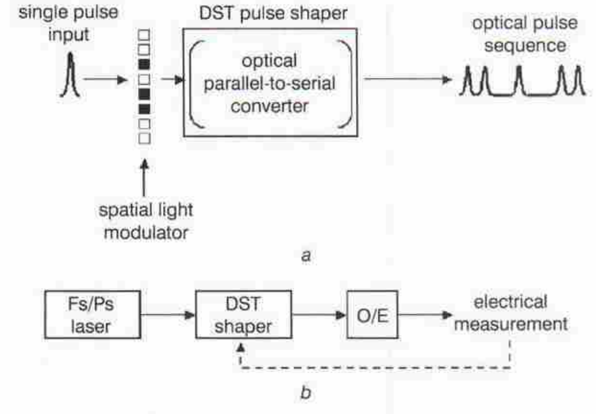

Fig. 1 *Schematic diagram and experimental diagram*

a Schematic operation of DST pulse shaper
Serial temporal output of DST shaper is a directly scaled version of applied parallel spatial pattern
b Experimental diagram
Smooth millimetre waveforms are generated from sequences of isolated pulses through optical-to-electrical conversion

Experiment: Direct space-to-time (DST) pulse shaping, in contrast to FT pulse shaping techniques, yields a temporal output which is a directly scaled version of a spatially patterned short pulse input [5].

Given the straightforward mapping from space to time, DST pulse shaping enables pulse sequence generation through simple manipulation of the applied spatial pattern. This is shown schematically in Fig. 1*a*. In this work, we utilised a novel DST shaper constructed for the first time in the 1.55 μm optical communications band. Our apparatus enables optical pulse sequence generation over a temporal window > 100 ps, which is ideal for generation of multi-cycle waveforms with centre frequencies in the range of multiple tens of GHz. Other novel features of our pulse shaper include the use of a diffractive optical element for spatial patterning and fibre coupled operation.

Our experimental setup is shown diagrammatically in Fig. 1*b*. The output from an actively modelocked erbium fibre laser [6], ~1 ps pulses at 10 GHz, is converted to pulse sequences in the DST shaper. These pulse sequences are in turn used to drive a 60 GHz photodiode, the output of which is measured on a 50 GHz sampling oscilloscope. The optical pulse sequence is predistorted as needed, e.g. to equalise the amplitude of the measured electrical waveform. The fundamental key to our experiment is to use pulse sequences where the pulses are spaced too closely in time to be completely resolved by the electrical measurement [4]. The limited bandwidth of the electrical system effectively filters harmonics in the optical pulse sequence, which generates smooth electrical sinusoids from isolated optical pulses. To achieve continuous electrical waveforms, the ability to perform pulse shaping over a temporal window of > 100 ps is combined with a source of comparable pulse period, allowing waveforms generated from individual source pulses, which span a ~100 ps frame, to be coherently stitched together with minimal error.

Results: Figs. 2 and 3 show continuous 50 GHz waveform generation; Fig. 2 shows the driving optical pulse sequences and Fig. 3 the resulting electrical waveforms. In (i), the measured electrical waveform is a smooth 50 GHz sinusoid. For this waveform, the spatial pattern in the DST is manipulated to give a five-pulse pattern with a pulse-to-pulse spacing of 20 ps and also to yield a spacing of 20 ps between the last pulse in one frame and the first pulse in the subsequent frame. In this manner, each 100 ps frame (delineated by the dashed lines) is created from one pulse from the optical source and stitched together with adjacent frames to generate a continuous 50 GHz waveform. Waveforms generated in our apparatus exhibit peak-to-peak amplitudes of ~20 mV, as determined by the optical excitation power and O/E conversion efficiency. Either wideband electronic amplification or increased optical excitation power could be used to increase the waveform power.

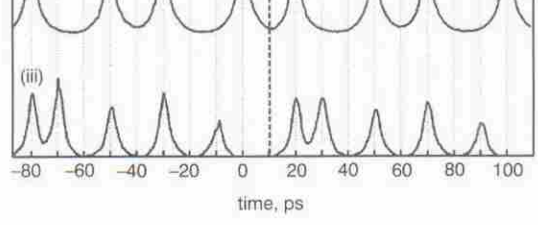

Fig. 2 *Driving optical pulse sequences*

(i) periodic 50 GHz pulse train
(ii) 50 GHz pulse sequence exhibiting extra 10 ps delay after first and third pulses
(iii) 50 GHz pulse sequence with single 100 GHz pulse pair

Examples of millimetre-wave phase and frequency modulation are shown in Fig. 2, (ii), (iii) and Fig. 3, (ii), (iii). Phase modulation of the electrical waveforms is achieved by adjusting the relative spacing of pulses in the driving optical pulse sequence (ii). The 50 GHz phase-modulated waveform shown in (ii) was generated by adding an extra 10 ps delay after the first and third pulses in each frame of the driving optical pulse sequence. This leads to a π phase shift at the corresponding temporal location, after the first and third cycles, in the electrical waveform. The phase shifts are easily seen by comparing the relative positions of the peaks and nulls with the periodic waveform of (ii). If we instead wish to frequency-modulate the waveform, we alter the relative pulse spacing within the driving optical pulse sequence. Illustrated in (iii) is a frequency-modulated waveform containing one 25 GHz cycle followed by three cycles at 50 GHz, with the modulated waveform repeating continuously every 100 ps as determined by the 10 GHz repetition-rate of the source laser. The single 25 GHz cycle is induced by the pulse pairs in the optical pulse sequence of (iii). Here the trick is to use pulses spaced too closely (~10 ps) to be individually resolved by the electrical system. The electrical responses from each pulse in the pair smear together yielding a cycle twice the duration of that for single pulse excitation. This is a clear illustration of the ability to generate continuous, periodic arbitrary millimetre-wave waveforms on a cycle-by-cycle basis.

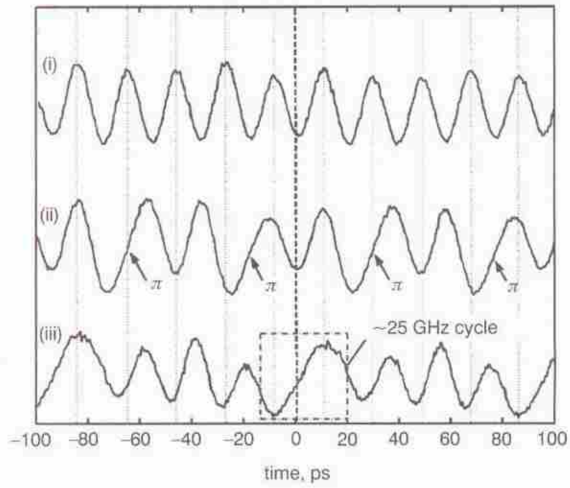

Fig. 3 *Continuous 50 GHz waveform generation*

(i) periodic 50 GHz waveform
(ii) phase-modulated waveform exhibiting π phase shift after first and third electrical cycles
(iii) 25/50 GHz frequency modulated waveform

Conclusion: We hence demonstrated the first continuous, periodic arbitrary millimetre waveform generation, at centre frequencies of 50 GHz, using a direct space-to-time pulse shaping technique. By altering the pulse period, spacing, and repetition-rate of pulses in tailored optical pulse sequences, we are able to synthesise periodic, phase-, and frequency-modulated electromagnetic waveforms on a cycle-by-cycle basis.

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All-fibre phase-aperture zone plates

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Fabrication of compact all-silica fibre Fresnel lenses based on a simple dielectric phase aperture zone plate, which can be spliced directly to standard singlemode optical fibre, is demonstrated. Image reconstruction of the field profile within the waveguide is demonstrated.

Introduction: A major industry component of optical devices is the compact lens that can be attached to the end of an optical fibre. Variations include ball lenses, gradient index lenses and similar devices. Ordinarily, when constructed into a working lens on the ends of standard singlemode fibres the full dimensions are rarely on the same 125 µm diameter scale. This can lead to undesirable complications in the arrangement and alignment of optical components. In addition, these components can add significant cost factors to the overall fabrication process involved with complex optical components and hence there is a need for cheaper alternatives compatible with standard fibres.

A recent alternative has been proposed and demonstrated where by careful fibre design a Fresnel lens can be etched onto a fibre end to achieve the same purpose [1]. However, precision fabrication of these components to improve coupling efficiency requires substantial modification of conventional fibre fabrication technologies. The graded ring layers involve ultra-precise layer deposition or control of complex boil-off processes. In this Letter, we propose a simpler alternative design based on air-silica structured fibres [2, 3] where the Fresnel lens is made up of appropriately sized aperture holes distributed along the Fresnel zones of a fibre. To our knowledge this is also the first example of an aperture array zone plate in a transmissive medium.

Fabrication: For the purposes of demonstration we fabricated a preform piece where the holes are drilled along virtual rings representing the Fresnel zones of the waveguide [3]. The dimensions and distribution are scaled down into a fibre 125 µm thick. This drawing phase was extremely sensitive to parameters such as temperature and draw speed. Therefore, the hole size, determined as a function of collapse, could be fine tuned accurately. Fig. 1 is a schematic diagram illustrating the lens spliced onto the standard fibre. A cross-section of the lens is also shown. In this particular example, the holes are placed along the Fresnel zones of the fibre; alternative designs can involve a range of hole sizes filling each zone similar to the array ring structures used in microwave transmission zone plates [4]. These designs tend to require numerical computation to optimise the hole size and distribution.

The zone distributions are close to the classical approximation where the area of each zone is constant and the radius of each zone is $r_n \cong r_0 + d^2/2r_0$ where r_0 is the radius of the central zone and d is the radius of the outermost zone. The equation holds when the effective Fresnel lens focus is a lot greater than r_0. The approximate modal field diameter for the fibre is chosen to be 30 µm. This could be tailored and fine tuned during fabrication by controlling temperature and fibre drawing conditions to control the hole size. A Fresnel lens based on apertures distributed on and within Fresnel zones is a well-known technology used in microwave signal processing [4]. Further, the extension of such a lens along an entire fibre has recently been proposed and demonstrated as a new form of waveguide guidance in air based on optical field superposition [5] and is based on ideas analogous to those described for controlling free-space diffraction [6, 7]. For practical lenses the fibre is spliced onto standard fibre and then cleaved to a dimension of a few millimetres or less.

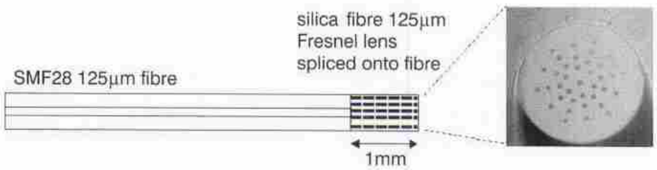

Fig. 1 *Schematic diagram of Fresnel lens cut into 1 mm length and spliced onto end of standard SMF28 fibre*

Cross-section of lens end shown on right

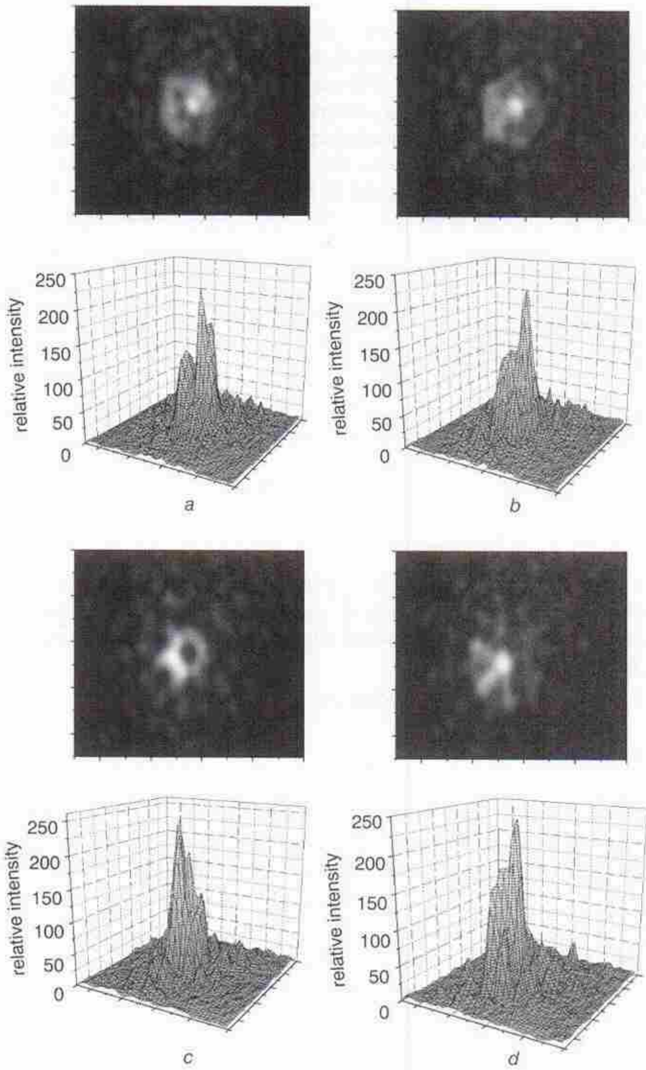

Fig. 2 *Field profiles at various positions at and away from fibre lens*

a Near-field profile at end face
b Field profile of first observable 'point' focus at ~30 µm
c Field profile of first observable 'ring' focus at ~130 µm where image reconstruction of central hole is observed
d Field profile of second 'point' focus at ~210 µm

Results and discussion: Results at 1550 nm for a 1 mm lens attached to singlemode SMF28 fibre are shown in Fig. 2. The near-field profile and the subsequent far-field profile at various distances are shown. A broadband erbium-doped fibre amplifier is used as the source. The profile changes from Gaussian-like to a ring distribution and back again. Each profile equates to image reconstruction of the optical fields which exist in the waveguide. Two effective foci of the fibre are observed consistent with the results expected for a Fresnel lens although the distance between them does not follow the traditional relationship seen from a conventional Fresnel lens: $f_n \sim r_0^2/n\lambda$ where n is an integer multiple, consistent with the multiple foci expected from Fresnel zone plates [8]. A factor of one half can be added when dealing with transmissive media and a graded zone plate. When $n = 1$, $f \sim 201$ µm; $n = 2$, $f \sim 100$ µm. We attribute this difference to several possible factors: (i) wavelength dispersion of the lens as a result of the broadband input from the EDFA, (ii) coupling into leaky modes over