Introduction: Terahertz (THz) waves have attracted considerable attention in the interdisciplinary fields of electronics and photonics for many applications such as high data rate transmission and high-resolution sensing, owing to the large available bandwidth and short wavelength compared to the microwave transmission [1, 2]. A resonant tunnelling diode (RTD) is one of the stronger enabling devices for developing compact THz systems with low power consumption [3]. It can operate as both an oscillator/transmitter and a detector/receiver by simply changing its operation bias voltage [4]. In recent years, various applications using THz RTDs have been reported including wireless communication [5, 6], sensing [7], and imaging [8].

To develop an advanced THz system, we have proposed and demonstrated the integration between an RTD and a two-dimensional photonic-crystal slab waveguide [9]. Furthermore, we have developed a 20 dB dielectric compact planar antenna integrated with a photonic-crystal waveguide for THz wireless transmission links [10]. However, free-space path loss (FSPL) will restrict the transmission distance due to the limited aperture size of the antenna. For 1 m links at the 0.3 THz band, the FSPL is estimated to be as high as ~40 dB.

In this Letter, we propose the application of a photonic-crystal integrated RTD device to a THz-fibre link for real-time communication and remote sensing. THz fibres using an air core and dielectric cladding structure have been studied for low loss, flexible, and robust transmission lines [11–16]. One of the critical issues to address before employing the THz fibre for applications is the coupling from free space into the fibre core. Here we demonstrate that a dielectric tapered structure integrated with a photonic-crystal waveguide is effective for coupling THz fibre with RTD devices. We perform THz fibre communications using an RTD transmitter (Tx) and receiver (Rx) at the 0.3 THz band. Finally, we demonstrate uncompensated 4 K high-definition video transmission through a 1 m-long THz fibre.

Device description and simulation: Fig. 1a shows the overview of the THz fibre transmission link using an RTD integrated with a photonic-crystal waveguide. The THz fibre comprised an air-core region surrounded by a thin and low refractive index expanded porous polytetrafluoroethylene (ePTFE) cladding layer. The propagation guiding mechanism is similar to that of a solid-core fibre [11, 12]. THz waves propagate not only through the air-core region, but also the cladding layer. That is, the fibre with the air core and air surrounding the fibre act as an effective core and as cladding, respectively. Since reducing the thickness of ePTFE cladding can decrease the effective refractive index, a thin cladding layer with a small inner diameter is required to ensure single mode and low-loss propagation. Therefore, we employ ePTFE with the refractive index of ~1.15. The inner diameter of the fibre and the cladding thickness are 280 and 220 µm, respectively, which can theoretically provide broadband transmission bandwidth (>100 GHz) and low propagation loss (~2 dB/m) at the 0.3 THz band.

We employ a 3 mm-long tapered structure [17] for a fibre coupler integrated with a photonic-crystal waveguide, as shown in Fig. 1b. The coupler is inserted into the THz fibre directly. The photonic-crystal waveguide consists of a 200 µm thick high-resistivity (20 kΩ/cm) silicon slab that contains a triangular lattice of circular air holes. The photonic-crystal waveguide is formed by introducing a line defect along the y − z plane. The lattice constant and radius of the etched holes were 240 and 72 µm, respectively, for 0.3 THz band operation. The minimum propagation loss is ~0.1 dB/cm for the 0.3 THz band [17].

We performed three-dimensional electromagnetic-wave simulations using a finite-integration method to investigate the coupling between the photonic-crystal waveguide and the THz fibre. The THz waves from the photonic-crystal waveguide are well coupled to the THz fibre via the tapered coupler as shown in Fig. 1c. Since the tapered structure has an adiabatic impedance changing from the THz fibre to the photonic-crystal waveguide, it can achieve high coupling efficiency and broadband operation. The simulated maximum coupling efficiency and 3 dB bandwidth are ~40% and ~80 GHz, respectively. We note that the simulated coupling efficiency between the typical RTD device for wireless communications integrated with a silicon lens [5] and the THz fibre is as low as ~0.01% because the size of the THz fibre core is smaller than half of the wavelength.

The RTD chip integrated with the photonic-crystal waveguide used here is shown in Fig. 1d. The RTD was grown on a semi-insulating InP substrate, and an GaInAs/AlAs double barrier structure formed the quantum well. The metallic tapered-slot coupling structure with an exponential characteristic profile provides an adiabatic impedance change from the RTD to the photonic-crystal waveguide to reduce the broadband reflection. As a result, high coupling efficiency (~50%) and broadband operation (~40 GHz) are achieved in practice [9].

Experiment: In order to experimentally characterise the coupling efficiency between the THz fibre and the photonic-crystal waveguides integrated with a silicon tapered coupler, we measured various lengths of the fibre. Transmittance in the range of 0.30–0.38 THz was measured by using a THz spectroscopic system based on a continuous wave (CW) electronic source using WR-3 hollow waveguides [17]. The CW source was implemented using a millimetre-wave signal generator and a nine-fold multiplier. Following propagation through the photonic-crystal waveguides and THz fibre, an identical photonic-crystal waveguide with a silicon tapered coupler is employed to collect the THz waves at the output. This output power was subsequently down-converted to a 404.4 MHz intermediate frequency by mixing with local-oscillator signals from a spectrum analyser. Fig. 2 shows the transmittance as a function of frequency. The observed propagation band corresponds to that of the photonic-crystal waveguide [17]. Both the simulation and experiment properties are in good agreement. From the transmittance for various fibre lengths, the propagation loss of present THz fibre and the coupling efficiency between THz fibre and a photonic-crystal waveguide for one port is estimated to be ~2 dB/m and ~30%, respectively. The 3 dB bandwidth of the transmission band is ~50 GHz. The slight discrepancy between simulation and experiment
seems to be due to the polarisation change during the propagation in the experiment.

We demonstrated THz fibre transmission links using RTDs integrated with photonic-crystal waveguides as a Tx and an Rx. The length of the photonic-crystal waveguide was 5 mm. The oscillation frequency and output power of the RTD Tx are 0.34 THz and 50 μW, respectively. The RTD Tx was on-off keying modulated using an arbitrary waveform generator, and direct-current biased voltage is supplied through a bias tee. The detected signal by the RTD Rx was amplified using a 33 dB gain pre-amplifier with a bandwidth of 18 GHz and was then waveform sharpened by a limiting amplifier. Fig. 3 shows the bit-error rate (BER) characteristic as a function of the data rate. Error-free transmission (BER<10⁻¹¹) was demonstrated up to 10 Gbit/s. The eye diagram was clearly opened at 10 Gbit/s.

Finally, we employed the THz fibre link system for uncompressed 4 K high-definition video transmission with a data rate of 6 Gbit/s [5] as shown in Fig. 4. In this experiment, we successfully demonstrated the THz fibre transmission link using the RTDs integrated with the photonic-crystal waveguides as Tx and Rx.

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One or more of the Figures in this Letter are available in colour online. X. Yu, M. Fujita and T. Nagatsuma (Graduate School of Engineering Science, Osaka University, 1-3 Machikaneyama, Toyonaka, Osaka 560-8531, Japan) E-mail: fujita@ee.es.osaka-u.ac.jp

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Fig. 2 Transmittance of THz-fibre links. The dashed black line shows simulation result of 1 0 m fibre link. The red, green, and blue solid curves denote experimental results on fibre lengths of 0.6, 0.8, and 1.0 m, respectively.

Fig. 3 Measured BER dependence on the data rate and the eye diagram at 10 Gbit/s.

Fig. 4 Uncompressed 4 K high-definition video transmission through 1 m-long THz fibre using a RTD Tx and Rx integrated with a photonic-crystal waveguide.