observed. The power penalty due to fibre dispersion for a 40 km standard fibre is only 0·3 dB, which is much smaller than that for the transmission systems using bulk-active DFB lasers. For the later case, the dispersion power penalty typically is larger than 1 dB. However, the result of using the strained MQW-DFB laser is only comparable with that of using the unstrained MQW-DFB laser.[12]

With a 60 km fibre included, the 1·7 Gbit/s transmission shows 0·8 dB dispersion power penalty for the use of the strained MQW-DFB laser. Since the dispersion power penalty is roughly proportional to the square of distance, we project that the dispersion power penalty will be in the range of 1·2–1·5 dB for using the laser in the 1·7 Gbit/s ASK transmission over an 80 km fibre.

Summary: We have reported the fabrication and the performance characteristics of 1·5 μm strained-layer MQW-DFB lasers. These lasers have narrower linewidth and lower chirp width than that of bulk-active DFB lasers. However, they are only comparable with unstrained MQW-DFB lasers, probably because of their positive detuning. A linewidth as low as 3·5 MHz was observed for one laser at 14·4 mW output. A 1·7 Gbit/s ASK transmission experiment using the strained MQW-DFB laser has been demonstrated with a receiver sensitivity of −37 dBm at BER = 10^{-9} and with 0·3 dB and 0·8 dB power penalty due to dispersion of 40 km and 60 km standard fibre, respectively.

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RESONANT-TUNNELLING DIODE OSCILLATOR USING A SLOT-COUPLED QUASIOPTICAL OPEN RESONATOR

Indexing terms: Tunnel diodes, Oscillators, Microwave oscillation

A resonant-tunnelling diode has oscillated at X-band frequencies in a microwave circuit consisting of a slot antenna coupled to a semiconfocal open resonator. Coupling between the open resonator and the slot oscillator improves the noise-to-carrier ratio by about 36 dB relative to that of the slot oscillator alone in the 100–200 kHz range. A circuit operating near 10 GHz has been designed as a scale model for millimetre- and submillimetre-wave applications.

The resonant-tunnelling diode (RTD) is a quantum-well structure which exhibits negative resistance that extends into the submillimetre-wave range. Fundamental-frequency oscillations at 675 GHz have recently been obtained from RTDs,[1] and detection experiments have demonstrated that the negative resistance responsible for these oscillators may persist to frequencies as high as 2·5 THz.[2] Planar circuits are more easily fabricated than waveguide circuits above 100 GHz, so a hybrid, planar, quasioptical RTD oscillator circuit whose essential features can be scaled for use at millimetre wavelengths have been developed. Instead of the customary reactive-network lowpass filter for biasing, a unique low-impedance, lossy transmission line has been used to isolate the RTD from external bias circuitry. A semiconfocal open cavity has also been used as a resonator, which allows very high quality factor Q and improves the spectral purity of the oscillator. Coupling of a microstrip line to an open resonator has been demonstrated.[3] This is the first time a planar oscillator has been coupled to an open resonator with a slot antenna.

The oscillator is illustrated in Fig. 1. A concave brass reflector faces a microwave circuit substrate that is clad with copper on the side facing away from the concave reflector. The separation distance, D, between the circuit and reflector is adjustable in the 15–20 mm range. The lowest-order (TEM_{000}) mode of the open resonator thus formed[4] is in the 8–10 GHz range. The Gaussian beam waist radius is 28 mm and lies well within the area of the 10 cm by 10 cm-square flat reflector as well as the larger spherical reflector, so diffraction losses are negligible. An unloaded Q of 3500 was measured for the TEM_{000} mode. This is a reasonable Q for a short open resonator.

The RTD was fabricated by molecular-beam epitaxy and has the material parameters, current–voltage characteristics, and the waveguide-oscillator performance described by Brown *et al.*[5] The resonant-tunnelling structure in the diode consists of two 1·5 nm-thick undoped AlAs barriers separated by a 4·5 nm-thick undoped GaAs quantum well. The GaAs regions outside each barrer were uniformly doped n-type with a concentration of $N_D = 2 \times 10^{17}\,cm^{-3}$. The current density and specific capacitance of this device are known from previous

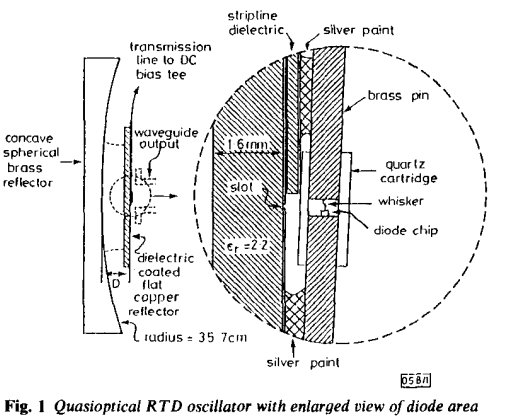

Fig. 1 *Quasioptical RTD oscillator with enlarged view of diode area*

measurements[5] to be $4{\cdot}5 \times 10^4\,\mathrm{A\,cm^{-2}}$ and about $1{\cdot}6\,\mathrm{fF}\,\mu\mathrm{m}^{-2}$, respectively, at the bias voltage for peak current (i.e. the low-voltage end of the negative-resistance region). The diode used in the present experiment was a $4\,\mu$m-diameter mesa with a peak current of 3·3 mA at a peak voltage of 0·7 V, and a peak-to-valley current ratio of about two at room temperature. The diode chip was mounted on a 0·6 mm-diameter post and inserted into a 2·5 mm-long quartz tube, where a tungsten whisker mounted on a similar post contacted the device (Fig. 1). Cyanoacrylate fixes the posts in the quartz tube. Although this package provides great convenience in handling, it has parasitic reactances that preclude its use above 30 GHz.

RTDs show negative resistance at all frequencies from DC up to the oscillation frequency. A bias circuit that suppresses undesired oscillations over such a broad frequency range presents a formidable challenge. The solution to this problem uses a lossy distributed element, rather than a low-loss reactive filter. Leading from the external low-frequency bias network to the diode circuit was a 6·3 mm-wide parallel-plate transmission line made from 0·25 mm-thick fibreglass circuit board material with copper cladding on both sides. The bias line accomplishes two things. It has a low characteristic impedance, $Z_0 \simeq 7{\cdot}5\,\Omega$, which provides for DC stability of the oscillator. It also presents a high loss (metallic and dielectric) per unit length, which significantly lowers the Q of all resonances in the bias circuit and thus prevents the occurrence of spurious oscillations in this circuit at frequencies below those of interest. The transmission line was 27 cm long, a length that approaches the ideal situation of an infinite line whose input impedance is Z_0, regardless of how the external bias circuit terminates the far end. At low frequencies, the transmission-line attenuation was insufficient for effective isolation, but normal termination and bypass measures with lumped-element networks at the bias end of the line prevented oscillations in that range of frequencies. In a monolithic version of this circuit, highly doped GaAs beneath a thin insulating layer could be used for the lossy dielectric. Metal-insulator-semiconductor slow-wave transmission lines have shown losses as high as 17·5 dB/cm at 5 GHz,[6] and this loss could easily be increased.

The diode package was placed in a circuit consisting of the diode, the parallel-plate bias line, and a slot in the single copper cladding of the resonator's flat reflector. The narrow dimension of the slot is shown in Fig. 1 and is approximately 0·13 mm. The wide dimension l runs perpendicular to the Figure and was about 6·3 mm. The equivalent circuit that best models the oscillator is shown in Fig. 2. At 8·9 GHz, the slot can be represented as an inductance L_s that is calculated to be about 1 nH. The semiconfocal cavity resonance occurs at a radian frequency $\omega_c = [L_r C_r]^{-1/2}$ and is represented by a series resonant circuit in which the energy storage is modelled by L_r and C_r, and the power losses are represented by R_r. The overall circuit resonance occurs at a frequency just below ω_c where the capacitive susceptance of the series resonant circuit cancels the inductive susceptance of the slot. At resonance, the cavity-slot circuit acts as an impedance inverter, transforming the resistance R_r into a higher resistance $R_s = (\omega L_r)^2/R_r$. For sufficiently high Q, R_s is large compared with the lossy line Z_0 at resonance, so that most of the current generated by the RTD is coupled to the external RF load, leading to smaller losses in the bias network.

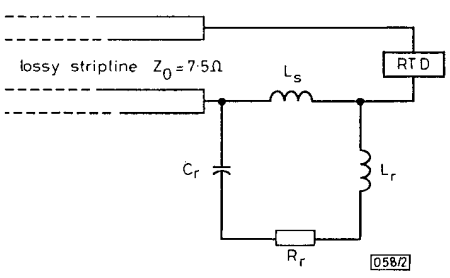

Fig. 2 *Equivalent circuit of slot-coupled, open-resonator oscillator*

Measurements were performed on the oscillator both with and without the open resonator in place. In both cases the output was monitored by means of an X-band waveguide flange that was placed as close as possible to the diode side of the slot. Although this coupling was rather inefficient, it was sufficient to permit spectral measurements.

The diode, its package parasitics, and the slot inductance form a low-Q resonant circuit that allows oscillation in the 8 GHz range in the absence of the spherical reflector. The spectrum is very broad, as the data for the no-resonator case in Fig. 3 shows. When the spherical reflector is moved into

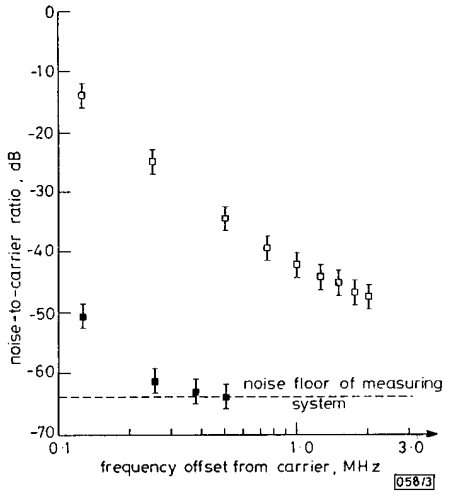

Fig. 3 *Noise-to-carrier ratio $\mathscr{L}(f)$ for RTD oscillator*
no open resonator ▮ open resonator

position and D is slowly varied so that the resonant frequency of the TEM_{000} mode sweeps past the free-running oscillator frequency, the oscillator locks onto the cavity mode. When locked, the noise-to-carrier ratio $\mathscr{L}(f)$ in the 100–200 kHz offset range decreases by about 36 dB, and the oscillator can be tuned over a 2·5% range by adjusting D. According to the elementary oscillator noise theory of Vendelin,[7] the value of $\mathscr{L}(f)$ (in the sideband frequency ranges not dominated by $1/f$ device noise) goes as Q_u^{-2} where Q_u is the unloaded quality factor of the resonant circuit. If Q_u with the open resonator is assumed to be 3500, the observed 36 dB decrease in noise would result if the slot-oscillator circuit Q_u was about 55. This value of Q_u is in the range to be expected from a planar-circuit oscillator. Although diodes of this type have produced as much as $150\,\mu$W in waveguide cavities, the unoptimised output power of this oscillator into the waveguide flange was only about $10\,\mu$W. This could be improved by a more sophisticated output coupling method such as the partially reflecting dielectric plate used by Popovic *et al.*,[8] in their quasioptical grid oscillator.

The quasioptical oscillator demonstrated can be scaled down in size for operation at millimetre and submillimetre wavelengths and could generate much higher power by incorporating many RTD slot-oscillators in a planar array. Fig. 4 shows a planar array of RTD slot oscillators in which the open resonator both synchronises the oscillator elements and narrows the linewidth. The lossy bias line feeds an entire row of such oscillators. In contrast to waveguide resonators, the Q of an open resonator of fixed size increases with frequency, so that this design should be very useful for the submillimetre-wavelength region.

The use of a quasioptical cavity and slot antenna as a resonator for an RTD oscillator has been demonstrated. The quasioptical cavity reduces the noise-to-carrier ratio by about 36 dB compared with the slot oscillator alone in the 100–200 kHz range. Variation of the cavity length leads to a 2·5% tunability of the oscillation frequency. This oscillator design is expected to be useful in the submillimetre-wavelength region

where the RTD has shown great promise as a fundamental solid-state oscillator.

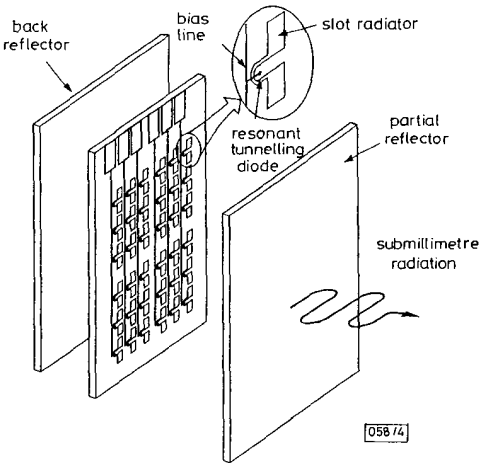

Fig. 4 *Planar-monolithic array of RTD oscillators synchronized by quasioptical cavity*

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CHIRP COMPENSATION CAPABILITY OF A SEMICONDUCTOR LASER AMPLIFIER

Indexing terms: Lasers and laser applications, Semiconductor lasers, Amplifiers

Performance improvement is reported resulting from incorporating a semiconductor laser amplifier (SLA) as a post-transmitter-amplifier in long-haul directly modulated optical systems operating in the 1·5 μm region. This improvement arises from reduction of the chirp produced by the semiconductor laser as the signal passes through the SLA. Eye closure penalty improvements in excess of 5 dB are observed for an illustrative long-haul 4·8 Gbit/s system.

Introduction: Long-haul high-data-rate direct-modulation optical-fibre communication systems, operating in the 1·5 μm wavelength region with conventional single-mode optical fibre, can be seriously impaired by interactions between laser dynamic frequency chirp and fibre chromatic dispersion. Insertion of a semiconductor laser amplifier as a post-transmitter amplifier enables the source laser to be operated at reduced power levels. This can help alleviate several problems associated with direct modulation of the semiconductor laser at high output powers, such as large chirp and the difficulty of implementing suitable drive circuits.[1] We show here that this configuration can also compensate for the frequency chirp of directly modulated lasers, thus improving the performance of long-haul systems. This happens because even with the modest peak power available from semiconductor lasers, the nonlinear properties of the SLA can be significant, yielding an amplified signal with an imposed frequency chirp, which counteracts the chirping of the directly modulated laser.[2]

System model and analysis: The block diagram of Fig. 1 shows the functional elements of a fibre-optic system using direct intensity modulation and post amplification. The optical source is assumed to be a DFB laser that is directly modulated by its drive current. The data patterns used are pseudo-

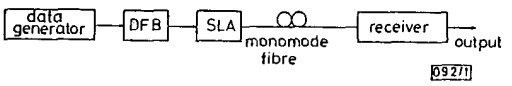

Fig. 1 *Block diagram of direct-detection optical communication system incorporating SLA as post-transmitter amplifier*

random sequences of length $2^5 - 1$. The response of the semiconductor laser in terms of optical power $P(t)$ and phase $\phi(t)$ is determined by solving the large-signal rate equations. The complex envelope of the electromagnetic field of the laser output can be represented by $E(t) = \sqrt{[P(t)]} \exp [j\phi(t)]$. The output field of the SLA, $E_{out}(t)$, taking into account the effect of facet reflectivities and gain saturation can be expressed in terms of the input optical field $E_{in}(t)$ and the physical parameters of the SLA:[3]

$$E_{out}(t) = t_2 t_1 E_{in}(t-\tau) \times \exp\left\{\tfrac{1}{2}G(t) - i\left[\frac{\alpha}{2}G(t) + KL\right]\right\} + r_1 r_2 E_{out}(t-2\tau) \times \exp\left\{\frac{G(t)+G(t-\tau)}{2} - i\left\langle\frac{\alpha[G(t)+G(t-\tau)]}{2} + 2KL\right\rangle\right\} \quad (1)$$

$$\frac{dG(t)}{dt} = \frac{G_0 - G(t)}{\tau_c} - \frac{t_2^{-2}|E_{out}(t)|^2}{E_{sat}}[1 - \exp(-G(t)] - \frac{r_2^2 t_2^{-2}|E_{out}(t-\tau)|^2}{E_{sat}}[\exp G(t) - 1] \quad (2)$$