

parameters can alter the stability of the system. Those three conditions are:

$$G_1^* G_2^* \leq 1/[(1 - K_1)(1 - K_2)] \quad (8a)$$

$$G_3^* \leq 1/(1 - K_2) \quad (8b)$$

$$G_1^* G_2^* G_3^* \leq 1/[K_2^2(1 - K_1)] \quad (8c)$$

where $G_i^* = f_i G_i(1 - \gamma)$, $i = 1, 2, 3$.

Some measurements have been taken, and they have been successfully tested with theory (Fig. 3), showing their capability of reshaping the spectral response because of the additional parameters they offer compared to single structures.

Conclusions: Double and single amplified recirculating delay lines have been described theoretically and experimental results have been reported. These configurations have successfully shown their flexibility of design to obtain different profiles depending on the choice of certain parameters: gain, loop length, and coupling ratios of the couplers. High peak to peak amplitudes and FWHM can be achieved. Different cases, to reflect the diversity of its possibilities, have been analysed. Their performance would be further improved by eliminating environmental hazards and stabilising the amplifier gain. Further analysis of double and more complex amplified recirculating structures can lead to a wider range of applications.

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DUAL-DEVICE ACTIVE PATCH ANTENNA WITH IMPROVED RADIATION CHARACTERISTICS

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Indexing terms: Antennas, Microstrip, Gunn oscillators

An active microstrip patch antenna for quasioptical power-combining arrays is described. The oscillator circuit uses two Gunn diodes which symmetrically load a resonant patch. The symmetry of the structure and the push-pull operation of the devices results in a dramatic decrease in H-plane cross-polarisation, improved copolarisation patterns, and twice as much power as a single-device patch.

Introduction: Arrays of coupled microwave and millimetre-wave oscillators offer an attractive method for combining the power from many solid-state devices. Such arrays have been demonstrated with a variety of different devices [1], and have been recently mode-locked for high-power pulse generation [2]. Each element of the array is a self-contained oscillator, built around a semiconductor device and a planar antenna.

Several different microwave oscillator circuits based on a microstrip patch antenna have appeared in the literature, using Gunn devices [3-4], IMPATTs [5-6], and FETs [7-8]. Millimetre-wave circuits using Gunn devices and slot antennas have also been reported [9]. The patch antenna is useful because it is simple to fabricate, can easily accommodate devices, and serves as a resonant stabilisation element in the oscillator circuit. In practice, however, active patch antennas with devices integrated directly inside the patch suffer very high crosspolarisation fields [3]. We report a modified active patch antenna, which is symmetrically loaded with two Gunn devices. This effects a significant reduction in crosspolarisation losses, results in more symmetrical copolarisation radiation patterns, and has the added advantage of doubling the available power from each array element.

Description: A commonly used active patch antenna circuit for two-terminal devices is shown in Fig. 1a. A Gunn diode

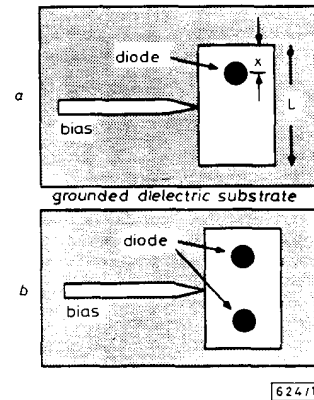


Fig. 1 Microstrip patch antenna loaded with single, active two-terminal device [3-4] and symmetrical, two-diode patch, which improves cross-polarisation and doubles the power

- a Microstrip patch antenna
b Two-diode

(or IMPATT) is integrated within the patch, shunting the top metallisation and the ground plane. The patch is designed to operate in the lowest-order resonant mode, with DC bias supplied to the device at null in the electric field under the patch. The design of these circuits proceeds semi-empirically, with the device located where the input resistance of the patch equals the negative resistance of the device. For a half-wavelength patch, the diode location can be found from the simple expression [4]

$$\frac{x}{L} = \frac{1}{\pi} \cos^{-1} \left[\frac{0.123W}{\lambda_0} \sqrt{|R_d|} \right]$$

where W is the patch width and R_d is the magnitude of the device negative resistance. The reactive impedance of the device will effect a change in the resonance frequency of the patch.

When the diode package occupies an appreciable fraction of the path volume (the usual case at X-band or higher), the actual current distribution on the patch will be quite different to that of a similar but deviceless patch. An excess of higher order current modes will be generated on the patch to account for this discontinuity. These higher-order modes are partially responsible for the high crosspolarisation observed in such active patch antennas. Asymmetry in the device location (again, the usual case) will further exacerbate this problem by exciting current modes with odd symmetry, resulting in asymmetrical copolar patterns. Another major contribution to the H-plane crosspolarisation arises from the vertical currents in the diode between the patch and ground plane (the 'feed' radiation).

Some of these problems can be alleviated through the use of a second diode, which is located diametrically opposite the

first as shown in Fig. 1b. This results in a symmetrical structure, which should correspondingly produce symmetrical copolar radiation patterns by suppressing the excitation of odd-symmetric high-order modes. Because the patch is operating as a half-wavelength resonator, the devices will operate in a push-pull mode [6], whereby the feed radiation from oppositely directed vertical currents in the two diodes will cancel out in the far field. Thus the H-plane crosspolarisation should be significantly reduced with this technique. The addition of a second diode would also be expected to change the frequency of the oscillation, owing to the additional reactance of the new devices.

Measurements: Two nearly identical active patch antennas were constructed to test these ideas, with one containing a single Gunn diode as in Fig. 1a, and the other with two devices as in Fig. 1b. Commercially available X-band Gunn diodes from MA/COM were used, which are capable of producing a minimum of 25 mW. The circuits were fabricated from 1.52 mm thick epoxy-resin circuit board ($\epsilon_r = 4.1$). Patch dimensions were selected as $9.8 \times 8.0 \text{ mm}^2$ for operation near 10 GHz. The cylindrical diode package had a radius of $\sim 1 \text{ mm}$.

Principal radiation pattern measurements for the single device oscillator are shown in Fig. 2. The circuit operated at a frequency of 10.4 GHz, with the device located 2.5 mm from a radiating edge and centred in the nonresonant dimension. Note the high crosspolarisation in the H-plane, and the deep scallop in the E-plane pattern at $\sim -20^\circ$. These are consistent with the earlier discussions. The abnormally high crosspolarisation in the E-plane is most likely caused by unwanted currents on the bias line, shown in Fig. 1: these could be eliminated by more careful design. The total radiated power was estimated from the principal patterns to be $\sim 26 \text{ mW}$.

With the addition of a second device diametrically opposite the first, the operating frequency changed to 10.7 GHz and the

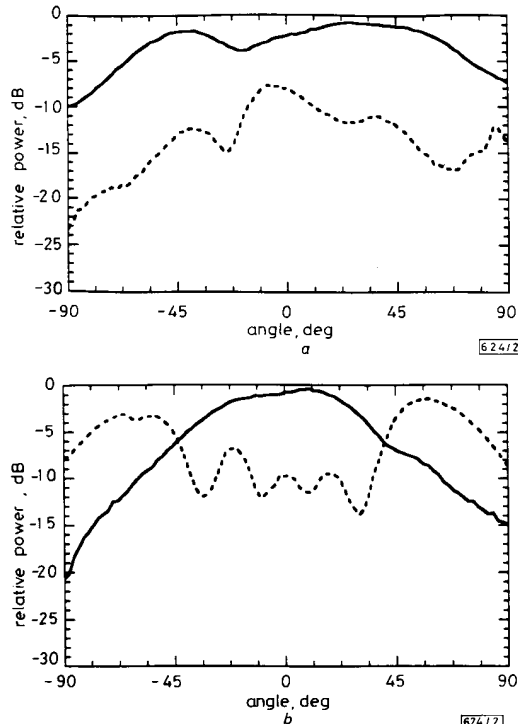


Fig. 2 Measured radiation patterns for single-device active patch operating at 10.4 GHz
 a E-plane
 b H-plane
 — copolar
 - - - crosspolar

principal radiation patterns shown in Fig. 3 were measured. As hoped, a significant reduction in the H-plane crosspolarisation was observed, along with more symmetrical

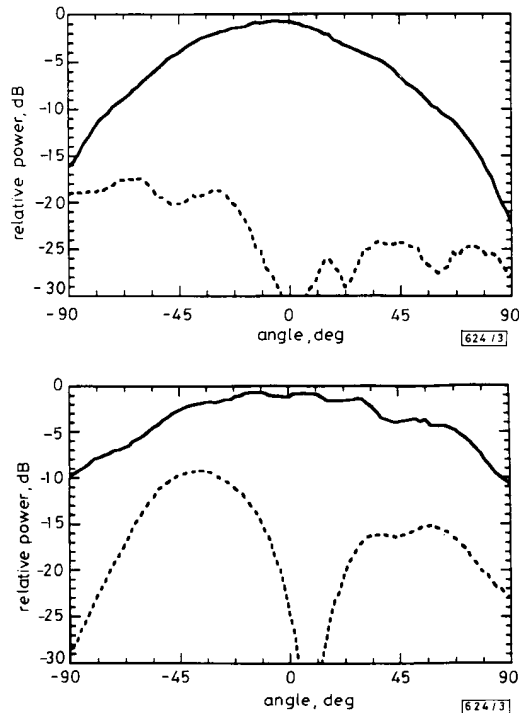


Fig. 3 Measured radiation patterns for dual-device active patch operating at 10.7 GHz

a E-plane
 b H-plane
 — copolar
 - - - crosspolar

copolarisation patterns. Note also the disappearance of the scallop in the E-plane pattern. The E-plane crosspolarisation changed qualitatively in an unexpected way, but did not increase in magnitude. A comparison of the effective radiated power (ERP) for the two circuits indicated that approximately twice as much power was obtained with this circuit.

Conclusions: The addition of a second device to a popular active patch antenna circuit had been shown to improve the radiation characteristics, producing symmetric copolarisation patterns and resulting in a dramatic decrease in the H-plane crosspolarisation. This circuit is expected to find application in quasioptical power-combining arrays, which would also benefit from the increased power available from each array element using this technique.

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NEW CLASS OF FIBRE LASER BASED ON LEAD-GERMANATE GLASS

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Indexing terms: Glass, Optical fibres, Lasers

The first fibre laser based on rare-earth doped lead-germanate glass is reported. The thulium-doped fibre had a background loss of 2 dBm^{-1} and a maximum phonon energy of $\sim 920 \text{ cm}^{-1}$. Lasing was achieved on the $\text{Tm}^{3+} \text{ } ^3\text{H}_4\text{-}^3\text{H}_6$ transition at $1.905 \mu\text{m}$ with a 3.6 mW threshold, when diode-pumped at 790 nm . A quantum efficiency of 30% was obtained.

We present a new class of rare-earth doped glass fibre which has been selected to have a maximum phonon energy of $\sim 920 \text{ cm}^{-1}$, a value intermediate between the maximum phonon energies of fluoride and silica-based glasses. Because of the high maximum phonon energy in silica glasses ($\sim 1150 \text{ cm}^{-1}$) [1] in many rare-earth doped silica glass fibre lasers the threshold for laser operation is limited by competition between multiphonon emission and radiative emission from the upper laser level. On the other hand, multiphonon emission is often essential in the pumping process because it provides the preferred channel for the decay from the pump level to the laser level. In these cases too low a phonon energy can result in a low pumping efficiency. An example of this effect is provided by the $^3\text{H}_4\text{-}^3\text{H}_6$ ($\sim 1.9 \mu\text{m}$) laser transition in Tm^{3+} (see Fig. 1). In ZBLAN, with its maximum phonon energy of 590 cm^{-1} [2], the $^3\text{H}_4\text{-}^3\text{H}_6$ transition has a high radiative quantum efficiency, but is limited by a low pump efficiency [3] to the $^3\text{H}_4$ level when diode-pumped via the $^3\text{F}_4$ level [4, 5]. By contrast, in silica the $^3\text{H}_4$ level has a low radiative efficiency but a high pump efficiency [6]. Thus for the $\text{Tm}^{3+} 1.9 \mu\text{m}$ laser, optimum laser performance would be achieved in a host with phonon energies low enough to ensure that the $^3\text{H}_4$ level decays purely radiatively, but high enough to ensure a high, phonon-mediated, transfer rate on the $^3\text{F}_4\text{-}^3\text{H}_5$ transition. Inspection of the equation for multiphonon decay in solids given by Layne *et al.* [7] indicates the optimum phonon energy required is $\sim 900 \text{ cm}^{-1}$. By using a modified lead germanate glass with a maximum phonon energy of $\sim 920 \text{ cm}^{-1}$, we can achieve the desired optimisation of the phonon energy. We show that in fibre form this results in a low-threshold laser with good slope efficiency. Furthermore lead-germanate fibre has the benefits of sufficiently low loss, high mechanical strength and a simple method of manufacture.

The lead germanate fibre was fabricated using the rod and tube technique [8]. The core glass was a proprietary lead-germanate melt with composition $\text{GeO}_2\text{-PbO-BaO-ZnO-}$

K_2O (abbreviated to GPBZK) and incorporating 0.5 wt% Tm_2O_3 , equivalent to $8 \times 10^{-21} \text{ ion cm}^{-3}$. The cladding was Schott SF56 glass. The experimental and theoretical considerations that lead to this core glass composition and choice of cladding glass will be reported elsewhere. Fibre was pulled

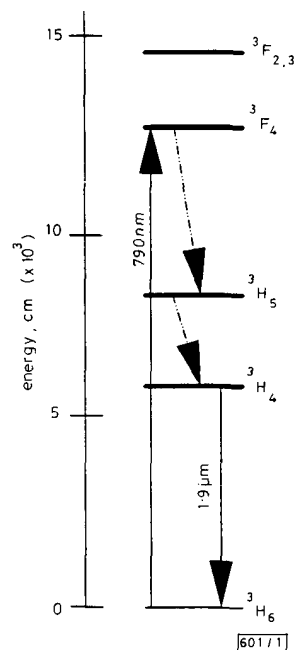


Fig. 1 Energy level diagram of Tm^{3+} in lead-germanate glass

Line positions were taken from bulk absorption spectra, and energy level assignment follows zero spin-orbit coupling convention

Excitation and lasing scheme for $\text{Tm}^{3+} 1.9 \mu\text{m}$ laser is shown

— radiative processes

- - - nonradiative, phonon emission, processes

with $7 \mu\text{m}$ core diameter and a total length in excess of 50 m . The fibre had good optical properties with a high quality homogeneous core-cladding interface. Because of the high dopant concentration and the high total absorption cross-section, the absorption at the peak of the $^3\text{F}_4$ pump band was $> 140 \text{ dBm}^{-1}$, and this allows lasers of only a few centimetres in length to be constructed. The high value for the absorption was due to both the high dopant concentration and the high absorption cross-section. The background fibre loss was 2 dBm^{-1} and probably represents the background loss the bulk glass used in the fibre core, which was limited by the purity of the starting materials. The mechanical strength of the GPBZK fibres was also good, with a bending radius of 5 mm possible in uncoated glass fibre, which is comparable with that obtainable in bare silica fibres.

The maximum phonon energy for the GPBZK core glass, as determined from the Raman spectrum of the glass, is given in Table 1, together with the measured $^3\text{F}_4$ and $^3\text{H}_4$ lifetimes for Tm^{3+} at 0.5 wt% in bulk glass. Equivalent figures are also given for ZBLAN and alumino-silicate fibre. Table 1 also gives the refractive indices of the various glasses. At $1.812 \mu\text{m}$ the refractive index of the GPBZK is substantially higher than for either silicates or fluorozirconates. Such a high refractive index yields two advantages, namely the possibility of producing very high numerical aperture fibres, further lowering the lasing threshold and increasing gain efficiency. Secondly a high refractive index yields an increase in the radiative probability and cross-section for a transition through the refractive index term in the Einstein coefficients [9].

Characterisation of the lasing properties of $\text{Tm}^{3+} : \text{GPBZK}$ fibre was carried out using Ti : sapphire or GaAs diode lasers as pump sources. In both cases laser cavities were constructed