

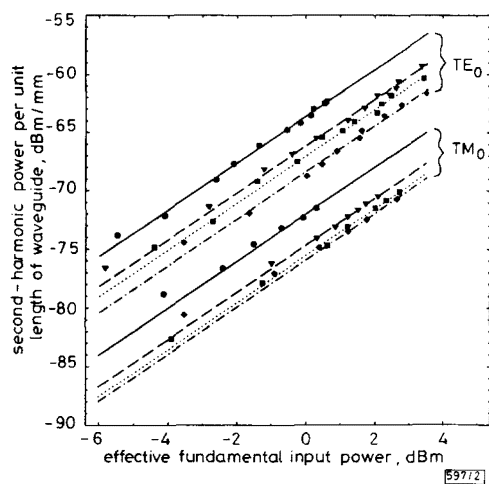


Fig. 2 Experimental plots of second-harmonic power per unit length of waveguide against effective fundamental input guided power for TE_0 and TM_0 mode excitation

Symbols: experimental values
Curves: square-law best fits
Four waveguide rib widths were tested
●, —, 1.6 μm
▲, ---, 2.8 μm rib
◆, ···, 4.6 μm

light onto a calibrated silicon photodiode. The oppositely propagating fundamental was generated by the reflection of the input signal at the cleaved waveguide output facet. The light emerging from the output facet was used to determine the fundamental guided power. Fig. 2 shows the results obtained for four different rib widths with TE_0 and TM_0 mode excitation. The waveguides were 1.14 mm long. The effective fundamental input power, $P_{\text{eff}}^{(\omega)}$, is given by $P_{\text{eff}}^{(\omega)} = [\sqrt{R}/(1-R)]P_{\text{meas}}^{(\omega)}$ where $P_{\text{meas}}^{(\omega)}$ is the measured fundamental power emerging from the output facet and R is the output facet power reflectivity. R was determined using the waveguide effective index in the Fresnel reflection formula. The quantity $P_{\text{eff}}^{(\omega)}$ allows the experimental situation to be compared directly with the theoretical analysis of [7] where there are two oppositely propagating unattenuated guided fundamentals of equal power.

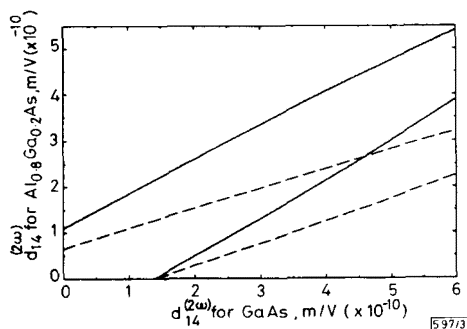


Fig. 3 Possible combinations of $d_{14}^{(2\omega)}$ for GaAs and $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$ that give best agreement between TE_0 mode (solid curves) and TM_0 mode (dashed curves) experimental conversion efficiencies of Fig. 2

— TE_0 mode
--- TM_0 mode

From the experimental data presented in Fig. 2, $d_{14}^{(2\omega)}$ for GaAs and $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$ can be deduced. Fig. 3 plots the possible combinations of $d_{14}^{(2\omega)}$ for GaAs and $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$ that give agreement between the TE_0 and TM_0 mode experimental conversion efficiencies and theoretical calculation. The latter follows the methodology described in [7] and takes into account the fundamental electric field distribution, material absorption at the harmonic frequency and the multiple reflections of the

harmonic at all the material interfaces. The material parameters used in the calculation were taken from [6]. Owing to the difference in fundamental electric field distribution between the TE_0 and TM_0 modes, two independent sets of solutions are obtained. The only intersection of the curves in Fig. 3 indicates a $d_{14}^{(2\omega)}$ of 4.59×10^{-10} m/V and 2.65×10^{-10} m/V for GaAs and $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$, respectively. The ratio of $d_{14}^{(2\omega)}$ between the two materials measured here is in good agreement with that obtained recently by the method of reflected second harmonics [9].

Conclusion: We have demonstrated a SESHG device grown on a (211)B substrate. This substrate orientation offers an up-conversion efficiency as good as that for a (110) substrate without the need for etched waveguide facets and, because only TE mode excitation is required, is suitable for active devices. From experimental data we have deduced values of $d_{14}^{(2\omega)}$ for GaAs and $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$.

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Heat-resistant singlemode optical waveguides using fluorinated polyimides

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Indexing terms: Optical waveguides, Integrated optics

Singlemode polymer optical waveguides are fabricated using fluorinated polyimides. The optical waveguides exhibit a low loss of less than 0.3 dB/cm parallel to the waveguide plane (TE polarisation) at 1.3 μm , and have thermal and moisture stability.

Introduction: Polymer optical waveguides are attractive for economical and practical optoelectronic devices and interconnections in optical communication systems [1, 2]. The first priority for such waveguides should be high thermal stability to provide compatibility with high-performance electronic device fabrication. Sullivan [3] fabricated thermally stable ridge waveguides with a loss of 0.3 dB/cm at 0.83 μm using polyimide. Hagerhorst-Trewhella *et al.* [4] have reported epoxy ridge waveguides with low loss (0.3 dB/cm at 1.3 μm) and high environmental and thermal stability (275°C). We have also reported ridge waveguides using fluorinated copolyimides with refractive index controllability, thermal stability, and moisture stability. These waveguides are multimode and have a low loss of 0.3 dB/cm at 1.3 μm [5], and have high enough thermal stability to be used in optoelectronic integrated circuits (OEICs). Optoelectronic multichip modules have been fabricated using these polyimide waveguides [6, 7]. However, singlemode waveguides will be needed for optical telecommunication systems in the near future. Imamura *et al.* [8] have fabricated a singlemode waveguide with a loss below 0.1 dB/cm at 1.3 μm by using deuterised and fluorinated poly(methyl methacrylate).

This Letter describes the first fabrication of singlemode optical waveguides using fluorinated polyimides, and also studies their optical loss and loss stability at 1.3 μm after treatment at high-temperature or in humid conditions.

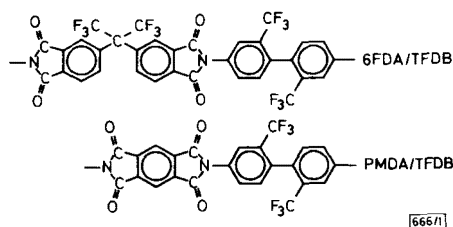


Fig. 1 Fluorinated polyimides for waveguides

Materials: The fluorinated polyimides used in this study are two kinds of homo-polyimide, 6FDA/TFDB and PMDA/TFDB (Fig. 1) and their copolyimides. Precise control of refractive index, which is singlemode waveguides consisting of core/cladding systems, can be achieved by changing the 6FDA/TFDB content [9]. The optical loss of 6FDA/TFDB has been estimated to be less than 0.1 dB/cm at 1.3 μm from the light absorption spectrum of polyimide solution [5]. The fluorinated polyimides have a high glass transition temperature above 335°C, and are thermally stable against the temperatures in IC fabrication processes involving soldering ($\sim 270^\circ\text{C}$). Conventional polyimides have high water absorption of around 2%, but our polyimides have low water absorption between 0.2 and 0.7% because of their high fluorine content. Low water absorption in waveguide materials is very important for stabilising optical properties.

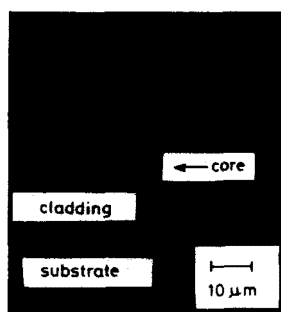


Fig. 2 Cross-section micrograph of embedded waveguide

Waveguide fabrication: Singlemode waveguides were fabricated using the polyimides by spin-casting, conventional photolithographic patterning, and reactive ion etching (RIE). An under-cladding layer and a core layer of the polyimides were formed on a

substrate. The core ridge was then fabricated by photolithographic patterning and RIE using oxygen. Finally, an over-cladding layer was formed. Fig. 2 shows a cross-section micrograph of the waveguide. The rectangular core ($8 \times 8 \mu\text{m}^2$) is completely embedded in the cladding layer. The refractive index difference between core and cladding is $\sim 0.4\%$, as measured from the interference micrograph.

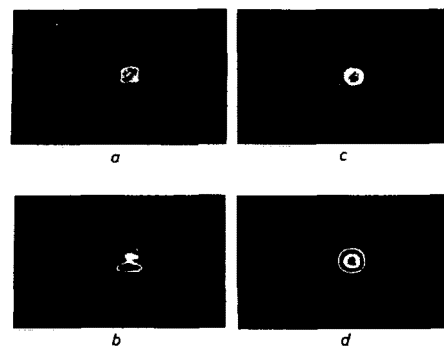


Fig. 3 Near-field mode patterns for 0.63, 0.85, 1.3 and 1.55 μm wavelength regions

a 0.63 μm
b 0.85 μm
c 1.3 μm
d 1.55 μm

Singlemode operation of the waveguides is identified from near-field mode patterns (NFPs). Fig. 3 shows NFPs of the waveguide for parallel waveguide plane (TE polarisation) at various wavelengths detected by a Hamamatsu C-1000 TV-camera. The NFPs show multimode behaviour at 0.63 and 0.85 μm , but show singlemode behaviour at 1.3 and 1.55 μm .

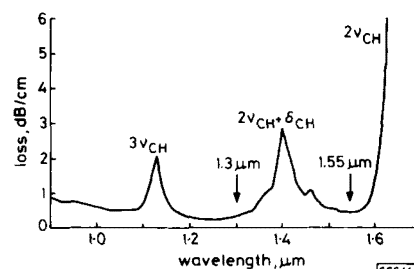


Fig. 4 Loss spectrum for waveguide

Optical loss: Fig. 4 shows the dependence of optical loss, including connection loss for TE polarisation on wavelength in the waveguide using an Advantest Q8381 optical spectrum analyser with a TQ8111 white light source. This spectrum is mostly similar to those of the polyimide materials. The optical loss based on the light absorption in the near-infrared region is mainly due to the harmonics and their coupling of stretching (ν) or deformation (δ) vibrations at chemical bonds. C-H bonds strongly affect the absorption. The spectrum has three absorption peaks due to the vibration of C-H bonds at 1.1, 1.4, and 1.65 μm . The wavelengths of 1.3 and 1.55 μm are located in the so-called 'windows'; there are no absorption peaks at these wavelengths.

Loss measurements were also performed using a laser diode as a 1.32 μm light source. The light was introduced into the waveguide using singlemode fibres with a modefield diameter of 8 μm . The input fibre was then precisely butted against the waveguide. Output light intensity was detected using an Anritsu ML9001A optical power meter with an MA9611A optical power sensor. The propagation loss is 0.27 dB/cm and the connection loss is 0.25 dB for TE polarisation measured using the cut-back method.

Loss stability against high temperature and humid conditions: After heating at 300°C for 1 h or exposure to 85% relative humidity at 85°C for 24 h, the increase in optical loss is less than 5%. This is

because these waveguides are fabricated by high temperature curing above 300°C and use low-water-absorption polyimides.

Conclusion: Heat-resistant singlemode optical waveguides were fabricated using fluorinated polyimides with excellent transparency and refractive index controllability. These optical waveguides have optical losses of less than 0.3dB/cm for TE polarisation at 1.3µm. The increase in optical loss is less than 5%, after heating at 300°C for 1h exposure to 85% relative humidity at 85°C for 24h.

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1.3 W CW, diffraction-limited monolithically integrated master oscillator flared amplifier at 863 nm

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Indexing terms: Semiconductor junction lasers, Optical amplifiers

High power, monolithically integrated master oscillator flared amplifiers are fabricated which operate at ~863 nm to an output power greater than 1.3W CW with a far field pattern consisting of a single, diffraction-limited lobe.

High power diffraction-limited semiconductor lasers are used for several applications including scientific investigations, frequency doubling, free-space communications and printing. Several methods have been pursued to achieve high power diffraction-limited operation. Monolithic active grating master oscillator power amplifiers (MAG-MOPAs) have been fabricated at both 980 and 1700nm [1, 2]. At 980nm MAG-MOPAs have achieved powers in excess of 0.8W with single diffraction-limited lobe output.

Antiguide lasers arrays have achieved CW output powers to greater than 1W, however, the fraction of power in the main lobe drops dramatically for output powers above 0.1W [3]. More recently, monolithic flared amplifier master oscillator power amplifiers (MFA-MOPAs) operating at ~980nm have achieved output powers greater than 3W CW with almost all of the power remaining in a single diffraction-limited lobe [4-6]. Similar results have been obtained with discrete flared amplifiers using a Ti:sapphire for a master oscillator [7].

Operation at wavelengths shorter than 980nm is beneficial for several applications. For example, operation at a wavelength between 810 and 870nm is preferred for free-space satellite communications to match the peak sensitivity of Si detectors. The highest CW power in a single diffraction-limited lobe from a semiconductor laser with a GaAs active region is ~0.2W [8]. In this Letter we demonstrate, for the first time, diffraction-limited operation to greater than 1.3W CW from an MFA-MOPA operating at 862.5nm. The high power output from the MFA-MOPA replicates the single frequency master oscillator and operates in a single longitudinal mode. In addition, the extinction ratio in the far field with the oscillator turned off is greater than 25dB.

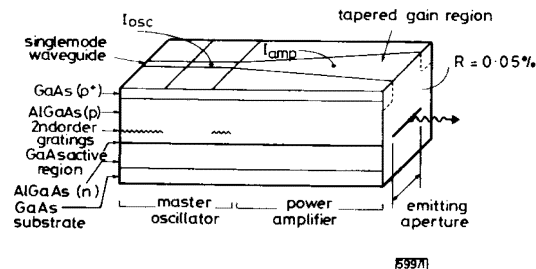


Fig. 1 Schematic diagram of monolithically integrated flared amplifier master oscillator power (MFA-MOPA)

A schematic diagram of the MFA-MOPA is shown in Fig. 1. The MFA-MOPA consists of a singlemode distributed Bragg reflector (DBR) master oscillator followed by a 2.5mm long flared amplifier which expands at an angle large enough to allow the free diffraction of the injected beam. Buried second order gratings are used to form the DBR laser. The gain section of the DBR laser is 750µm long.

The epitaxial structure used in this work is grown by a two step metal organic chemical vapour deposition (MOCVD) process. The optical waveguide is a standard AlGaAs separate-confinement heterostructure with a GaAs quantum well active region. The first epitaxial growth is halted just after a portion of the p-side AlGaAs cladding is grown and removed from the reactor. The second order gratings are fabricated using standard photolithographic and holographic techniques. After grating formation, p-type cladding and capping layers are grown by MOCVD. The grating teeth are approximately 65nm high. The modal overlap with the gratings is estimated to be 2.8% and the modal overlap with the GaAs quantum wells is ~4.5%. The DBR master oscillator is an approximately 4 µm wide index-guided structure. Antireflection (AR) coatings with reflectivities of the order of 0.1% are deposited on both the output facet and the facet formed behind the rear grating of the DBR master oscillator. The master oscillator and amplifier are contacted separately. In addition, devices are mounted p-side down on high thermal conductivity heatsinks for efficient CW operation.

A plot of CW optical power against injected amplifier current (L-I) is shown in Fig. 2 for the MFA-MOPA. These data are taken at a heatsink temperature of 15°C with 90mA of current to the DBR master oscillator. The L-I curve remains linear with a slope efficiency of 0.64W/A (45%) to an output power in excess of 1.7W CW.

The spectral output of the MFA-MOPA is a single longitudinal mode at a wavelength of 862.5nm. An optical emission spectrum taken at an output power of 1.31W is shown as an inset in Fig. 2. The optical emission spectrum indicates single longitudinal mode operation. The full width at half maximum (FWHM) is 0.3Å, the resolution limit of the spectrometer. Separate measurements indicate a sidemode suppression in excess of 20dB. The wavelength of