The waveguide is constructed on a GaAs substrate. By reducing $d$ the thickness of the lower 20% AlGaAs cladding layer, which separates the guiding region from the high index layers (see Fig. 1) we can selectively increase the loss of the higher order modes, resulting in a single low-loss mode. This is illustrated in Fig. 2, which is a plot of attenuation {imag($\beta/k_O$) where $k_O = 2\pi/\lambda$ and $\lambda$ is the free space wavelength and $=1.064\mu m$ } against $d$ for the three TE modes. Choosing 1dB/cm (imag($\beta/k_O$)< $-0.6 \times 10^{-5}$) as a allowable maximum loss value, we see that for $d = 0.4\mu m$ we have effectively only one low-loss mode.

Fig. 3*a-c* are contour plots of the modulus of the real part of $E$ for each of the three TE modes at $d = 0.4\mu m$. The plots clearly illustrate the increased power radiated into the substrate for the higher order modes.

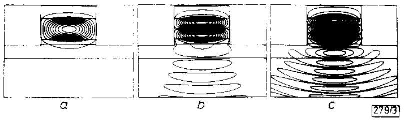

**Fig. 3** *Field amplitude (modulus of real part) contours at intervals of 10% of maximum for structure in Fig. 1 for d = 0.4μm*

*a* $TE_0$ $\beta/k_0 = 3.5738000 - j\,0.169681 \times 10^{-6}$
*b* $TE_1$ $\beta/k_0 = 3.5432314 - j\,0.548104 \times 10^{-4}$
*c* $TE_2$ $\beta/k_0 = 3.4942785 - j\,0.884144 \times 10^{-3}$

In this Letter we are investigating the elimination of higher-order vertical modes. However, preliminary calculations suggest the existence of a number of higher-order lateral modes. This will be the possible subject of a further publication.

In conclusion, we have performed the first study of leaky modes in two dimensional rib waveguides and have shown that the leaky nature of the modes can be exploited to control the number of low-loss vertical modes supported by the structure.

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G. M. Berry and S. V. Burke (*Department of Physics and Astronomy, University of Wales College of Cardiff, PO Box 913, Cardiff CF2 3YB, United Kingdom*)

J. M. Heaton and D. R. Wright (*Defence Research Agency (DRA), Electronics Division, St. Andrews Road, Great Malvern, Worcestershire WR14 3PS, United Kingdom*)

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# Diffusion-bonded stacked GaAs for quasi-phase-matched second-harmonic generation of a carbon dioxide laser

L. Gordon, G.L. Woods, R.C. Eckardt, R.R. Route, R.S. Feigelson, M.M. Fejer and R.L. Byer

*Indexing terms: Gallium arsenide, Optical harmonic generation, Gas lasers*

The authors have fabricated a diffusion-bonded monolithic stack of GaAs plates for quasi-phase-matched second-harmonic generation of a 10.6μm $CO_2$ laser. This synthetic nonlinear crystal retains the thermomechanical properties of the bulk material, and has provided phase coherent nonlinear interaction over ~0.4cm.

High average power coherent sources are needed throughout the infra-red and nonlinear frequency conversion of existing lasers can provide these sources. However, currently available infra-red (IR) nonlinear materials (e.g. the chalcopyrites $AgGaS_2$, $AgGaSe_2$, and $ZnGeP_2$) are limited by low surface damage thresholds, large absorption coefficients, or low thermal conductivity [1,2]. GaAs and ZnSe have high thermal conductivities and low absorption coefficients, and are widely used for windows and mirrors in high-power IR laser systems. These cubic crystals also have large second-order nonlinear susceptibilities; however, they cannot be birefringently phasematched, and, therefore, have not been used in practical frequency conversion applications.

An alternative to birefringent phase matching is quasi-phase-matching (QPM) [3,4,5], where a periodic modulation of the nonlinear susceptibility compensates for the phase velocity mismatch between the interacting waves. Stacks of discrete plates at the Brewster angle have been used to quasi-phase-match second-harmonic generation (SHG) in GaAs [6,7] and CdTe [8], but reflection and scattering losses associated with the many interfaces in the air-spaced layers precluded wide-spread application. Although thin plates (250μm) of $LiB_3O_5$ have been optically contacted with good results [9], the high indices of refraction of III-V semiconductors lead to significant losses for optical contacting wafers with practical polishing tolerances [6].

To eliminate the air-semiconductor interface problems, we diffusion bonded the adjacent layers to create a monolithic structure. Diffusion bonding has previously been used both for joining dissimilar semiconductors for optoelectronic devices [10,11] and for fabricating laser slabs with nonuniform doping [12]. We report here the fabrication and nonlinear optical testing of diffusion-bonded stacked (DBS) GaAs for 10.6 – 5.3μm second-harmonic generation.

A variety of undoped and lightly doped GaAs wafers were used. They were all mechanical grade and polished on both sides. The wafers were diced into $1cm^2$ pieces. The pieces were cleaned thoroughly with trichloroethane, followed by acetone and finally methanol. They were then stacked in a boron nitride holder between graphite spacers. Pressure was applied with a 1kg weight, and the assembled stack was placed in an oven with a 5% $H_2$ and 95% $N_2$ atmosphere. The temperature was ramped to 840°C over one hour. After maintaining that temperature for two hours, the oven was cooled to room temperature over approximately eight hours.

Stacks with 2–9 layers were bonded into monolithic units. The samples cleaved along the crystal planes leaving the bonded surfaces intact. We were able to bond wafers regardless of their dopings, their alignment of crystalline axes and their orientations: {100} to {100}, {110} to {110} and {110} to {100}. The exterior surfaces of the stack, which were in contact with the graphite spacers, were noticeably degraded after the processing. We did not repolish these surfaces, as the resulting uncertainty in the layer thicknesses would have hampered analysis of the SHG results.

The {110} wafers were chosen for the SHG studies because they provided the maximum effective nonlinear coefficient in GaAs for propagation normal to the input face. Adjacent wafers were rotated by 180° to alternate the sign of the effective nonlinear coefficient. The dispersion equation [13] predicts a coherence length, $L_c$, of 106μm for doubling 10.6μm radiation in GaAs. Available {110} wafers were 435μm thick (±5μm). Although this thickness was adequate for intial testing of the diffusion bonding technique, it was not an odd multiple of $L_c$ and, therefore, not optimal for SHG at 10.6μm.

Five samples, with 2, 3, 5, 7, and 9 layers were characterised, and compared to a single plate. Linearly polarised 10.6μm radiation from a grating-tuned, 200ns, Q-switched $CO_2$ laser was incident normal to the DBS GaAs sample with approximately 2 MW/cm² peak intensity. Second-harmonic output power at 5.3μm was measured with an InSb detector. The fundamental polarisation was fixed along a <111> direction.

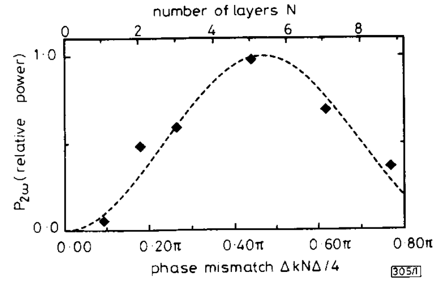

**Fig. 1** *Second harmonic output power, $P_{2\omega}$ of $CO_2$ laser as function of phase mismatch and number of layers in diffusion-bonded quasi-phase-matched GaAs structures*

◆ data
--- sin² fit

Fig. 1 shows the relative SHG power for diffusion bonded stacks of two, three, five, seven and nine layers, as well as for a single plate. The measured thickness of the wafers was used to calculate the total phase mismatch as a function of the number of layers, $N$, and the output power was compared to the expected $\sin^2(\Delta k N\Lambda/4)$ dependence, where $\Delta k \equiv k_{2\omega} - 2k_\omega - K_m$, and the wave vector due to the QPM grating is $K_m = 2\pi m/\Lambda$ . Here $k_\omega$ and $k_{2\omega}$ are the wave vectors for the fundamental and second-harmonic frequencies, respectively. The period of the modulation, Λ, is twice the wafer thickness. The integer $m$ is the order of the QPM [5]. The agreement with the expected dependence on the number of layers demonstrates that the DBS GaAs acts as a monolithic structure with a modulated nonlinear coefficient, providing a phase coherent interaction.

Many potential applications of these DBS GaAs structures involve frequency conversion at high average and high peak power. Some preliminary damage measurements were therefore performed. We exposed both the bulk and DBS GaAs to increasingly higher intensities for up to 5 min and then examined the samples under a microscope for damage. A 26W CW $CO_2$ laser beam was focused to a ~60μm 1/e² radius spot, producing an intensity of ~500kW/cm². No damage was detected, whereas $AgGaSe_2$ damages at 5–60kW/cm² with a CW $CO_2$ laser [1]. A 1kHz pulsed $CO_2$ laser with 60 – 500μs pulse width was focused to a peak intensity of 30MW/cm². No damage was seen in the bulk GaAs. We were unable to obtain accurate data from the DBS GaAs at this power level because the degraded outer surfaces developed damage characteristic of thermal runaway. However, the samples were not noticeably damaged with a single pulse, whereas $AgGaSe_2$ is damaged at ~10MW/cm² for 80–180 ns pulsed operations [2].

DBS GaAs has very large acceptance bandwidths due to noncritical phase matching and high index of refraction with low dispersion [13]. For a 1cm long structure for SHG at 10.6μm (~94 layers), the FWHM wavelength acceptance is 0.5μm, and the temperature acceptance is 270°C. The external angular acceptance is 64° FWHM. Because GaAs is not birefringent, there is no birefringent walk-off at any incidence angle, and QPM produces no phase-velocity walk-off at normal incidence [5].

Variations on the basic structure can be fabricated. Fig. 2*b* shows a structure with {100} oriented cap layers. For this orientation there is no effective nonlinear coefficient at normal incidence. Because the thickness of these cap layers is not important, this structure could be repolished, without compromising the conversion efficiency. QPM allows novel designs not possible with birefringent phase matching. For example, the structure shown in Fig. 2*c*, composed of wedged wafers, allows wavelength tuning by translation instead of by rotation. Caps could be added to this structure eliminating any overall linear wedge, thus avoiding beam steering effects. Such structures would be particularly useful for mid-IR optical parametric oscillators and mixers.

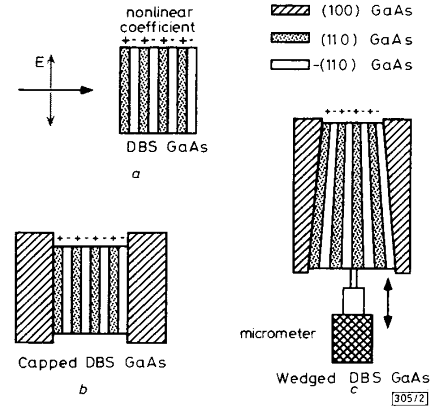

**Fig. 2** *Proposed diffusion-bonded-stacked (DBS) GaAs devices*

*a* Basic DBS GaAs structure that was fabricated and tested
*b* Basic structure with {100} GaAs cap
c Wedged DBS GaAs structure which allows wavelength tuning by translation

These preliminary results indicate the feasibility of fabricating DBS structures. We were able to fuse wafers to form monolithic crystals, with bond strengths comparable to the bulk material. We measured SHG nonlinear conversion which followed theoretical predictions. We also determined that the damage thresholds are at least 500kW/cm² for CW and 30 MW/cm² for peak power at 10.6μm. Current work includes polishing the layers to the correct thicknesses, and repolishing the devices after processing, increasing the numbers of layers to improve conversion efficiency and testing for damage thresholds at different wavelengths, and with higher power lasers. In the future, the DBS processing techniques may be extended to other nonlinear crystals such as ZnSe to take advantage of different material characteristics, and to other applications such as difference frequency generation or parametric devices for tunable infrared generation.

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L. Gordon, G. L. Woods, R. C. Eckardt, R. R. Route, R. S. Feigelson, M. M. Fejer and R. L. Byer (*Center for Nonlinear Optical Materials, Stanford University, Stanford, CA 94305, USA*)

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# High modulation frequency low distortion 1.3 μm MQW-DFB-LDs for subcarrier multiplexed fibre-optic feeder systems

H. Yamada, T. Okuda, M. Shibutani and S. Tomida

*Indexing terms: DFB lasers, MQW lasers, Subcarrier multiplexing*

A remarkable improvement has been attained for intermodulation distortion and spectrum linewidth performance for 1.3μm DFB LDs by introducing thin barrier MQWs and short cavity configurations. Less than –85dBc in 3rd order intermodulation distortion and more than 50MHz in spectral linewidth have been simultaneously obtained from devices modulated by two 1.5GHz signals.

*Introduction:* High capacity subcarrier multiplexing (SCM) [1,2] has recently emerged as an attractive technique for fibre-optic loop applications, such as CATV and microcellular mobile communication systems [3]. It is important to realise low harmonic and intermodulation distortion LDs at modulation frequencies beyond the gigahertz level to meet requirements for increasing numbers of channels and subscribers. In particular, the microcellular fibre-optic feeder requires wide dynamic range to receive widely varying RF signals from mobile stations, thus distortion and noise must be suppressed to an extremely low level. For example, less than –75dBc in 3rd order intermodulation distortion $IMD_3$ will be required for the pan-European GSM type 8 channel TDM system at up to 1.5GHz [3]. Because the distortions are caused by the resonance effect between carriers and electrical fields in laser cavities, a high relaxation oscillation frequency $f_r$ is required in LDs [1]. Furthermore, wide spectrum linewidth $\Delta\nu$ performance is also desired for the system to suppress the beat noise caused by multiple optical reflections from optical fibre connectors [2].

In this Letter, we propose a thin barrier and short cavity MQW-LD, in order to achieve both extremely low $IMD_3$ beyond gigahertz frequencies and wide $\Delta\nu$ performance. Fabricated 1.3μm MQW-DFB-LDs possessed >10 GHz $f_r$, $IMD_3$<–85dBc at 1.5GHz and $\Delta\nu$>50MHz, which is the first demonstration of a device suited for high frequency modulated fibre-optic feeder applications.

*Device structure:* A thin barrier MQW structure was employed in order to relax the nonuniform carrier-injection in each well and to improve $f_r$. MQW wafers used were grown by low-pressure metal-organic vapour-phase epitaxy (MOVPE). Fig. 1 shows an active region band diagram for fabricated MQW structures consisting of 10 InGaAsP ($\lambda_g$ = 1.40μm) wells, separated by InGaAsP ($\lambda_g$ = 1.13μm) barriers. To investigate the dependence of $f_r$ on barrier thickness, the barrier thicknesses were varied from 30 to 100Å.

A conventional DC-PBH structure, with a 1.5μm mesa width, was adopted as a current-blocker, and the wafer was then cleaved into 200μm long cavity. Less than 1% antireflective mirrors and 75% highly-reflective mirrors were formed on the front and rear facets, respectively. The κ*L* value is assumed to ~1 for 200μm devices. To obtain high differential gain, the Bragg wavelength was detuned by 10 – 15nm shorter than the gain peak wavelength.

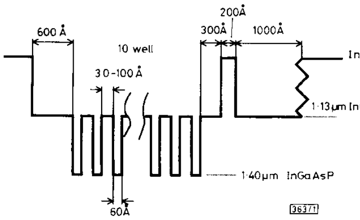

**Fig. 1** *Schematic band diagram of active region*

*Device characteristics:* Typical threshold current $I_{th}$ and slope efficiency $\eta_s$ were 16mA and 0.42W/A for the devices with 30Å thick barriers. The $I_{th}$ and $\eta_s$ values were almost independent of barrier thickness, suggesting that the quantum well effect apparently does not degrade with decreasing barrier thickness. More than 40dB in sidemode suppression ratio (SMSR) was obtained under 1.5GHz two-tone modulation.

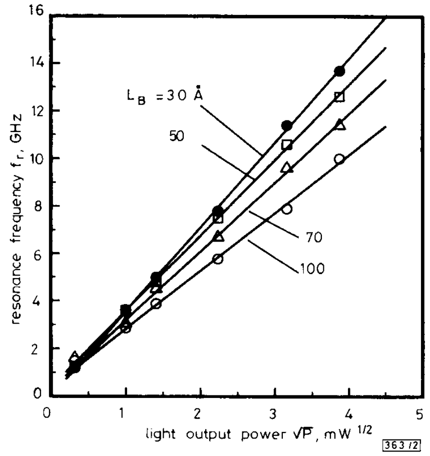

**Fig. 2** *Light output power dependence of resonance frequency*

Fig. 2 shows the light output power dependence of $f_r$ for the LDs with different barrier thicknesses measured from the RIN spectra. As seen in Fig. 2, $f_r$ increases with decreasing barrier thickness. $f_r$ . 14GHz was obtained from a device with 30Å thick barriers at 15mW output power, although the $f_r$ for a device with 10Å thick barrier was only 10GHz. This result is attributed to the increased differential gain possibly due to the relaxation of carrier localisation in the MQW by the thin barrier structures. This result suggests that gain suppression due to finite carrier capture time in barrier regions [4, 5] and/or unequal carrier distribution between the different wells is reduced by decreasing the barrier thickness [6].

Third-order intermodulation distortion $IMD_3$ was measured at 1499.8MHz and 1500.4MHz for LDs modulated by 1500.0 and 1500.2MHz signals. The optical modulation index OMI was 20%