Mid-IR laser source using hollow waveguide beam combining

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ABSTRACT

Hollow waveguide technology is a route to efficient beam combining of multiple laser sources in a compact footprint. It is a technology appropriate for combining free-space or fibre-coupled beams generated by semiconductor, fibre or solid-state laser sources. This paper will present results of a breadboard mid-IR system comprising four laser sources combined using a hollow waveguide optical circuit. In this approach the individual dichroic beam combiner components are held in precision alignment slots in the hollow waveguide circuit and the different input wavelengths are guided between the components to a common output port. The hollow waveguide circuit is formed in the surface of a Macor (machinable glass-ceramic) substrate using precision CNC machining techniques. The hollow waveguides have fundamentally different propagation characteristics to solid core waveguides leading to transmission characteristics close to those of the atmosphere while still providing useful light guidance properties. The transmission efficiency and power handling of the hollow waveguide circuit can be designed to be very high across a broad waveband range. Three of the sources are quantum cascade lasers (QCLs), a semiconductor laser technology providing direct generation of midwave IR output. The combined beams provide 4.2 W of near diffraction-limited output co-boresighted to better than 20 µrad. High coupling efficiency into the waveguides is demonstrated, with negligible waveguide transmission losses. The overall transmission of the hollow waveguide beam combining optical circuit, weighted by the laser power at each wavelength, is 93%. This loss is dominated by the performance of the dichroic optics used to combine the beams.

Keywords: Mid-IR laser, quantum cascade laser (QCL), Ho:YAG solid-state laser, hollow waveguides, integrated optics, beam combination

1. INTRODUCTION

High brightness laser sources operating in the mid-infrared (wavelengths 2-5 µm) region of the electromagnetic spectrum are of interest for a wide range of applications encompassing medical, defence and remote sensing. Directed Infrared Countermeasure (DIRCM) systems are used to protect airborne platforms from IR-guided ('heat-seeking') missile threats, the primary threats in this class being Man Portable Air Defence Systems (MANPADs). They operate autonomously by detecting a missile launch, determining if it is a threat and activating one or more effectors which track its approach and direct a modulated beam of laser energy to defeat it. The modulated beam is directed at the missile seeker, jamming it and driving the missile away from the aircraft. This all occurs within a matter of seconds and these lasers have to operate in a challenging physical environment with demanding constraints in size, weight and power (SWaP).

Mid-IR lasers have been, and continue to be, an active area of academic, industrial and military research interest and there have been a number of significant and relevant technology developments over the last decade, particularly in the area of fibre and semiconductor lasers. The general requirements and relevant laser technologies for DIRCM are reviewed in several papers [1],[2],[3].

In this paper we present details of two novel technologies pertinent to next generation DIRCM sources, namely hollow waveguides and quantum cascade lasers.

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Hollow waveguides have fundamentally different propagation characteristics to solid core waveguides. The hollow core leads to transmission characteristics close to that of the atmosphere whilst still providing light guidance. As a consequence the operational waveband is significantly broader than for a solid core waveguide, as is the optical power density which can be supported. Furthermore, there is no refractive index interface between free-space and the hollow core, so there is no interface reflection or loss. As a result it is easy to integrate discrete components into a hollow waveguide optical circuit e.g. dichroic elements for spectral beam combining and/or power scaling of discrete laser sources. Common boresight of the combined laser outputs is inherent to this design.

The quantum cascade laser (QCL) is a semiconductor laser technology offering efficient, direct emission over a wide range of wavelengths across the mid and far-IR wavebands. Since their first demonstration in the 1990s there have been rapid developments in power scaling, efficiency and wavelength coverage. There have been two relatively recent reviews of QCL technology covering their development, performance and application [4],[5]. In terms of output power in the mid-IR, the group at Northwestern University recently reported 5.1 W continuous wave (cw) output from a room temperature single emitter chip operating at a wavelength of 4.9 µm [6]. This equates to an electrical-to-optical conversion efficiency of 21%. No details of the beam quality are provided, but the single emitter ridge width of 8 µm implies that the output beam should be close to diffraction-limited.

A number of QCL sources are necessary to provide the spectral coverage required for the DIRCM application, hence our interest in the use of a hollow waveguide beam combiner (HWBC) optical circuit.

2. HOLLOW WAVEGUIDE BASICS

Figure 1 illustrates a square cross-section hollow waveguide of width w. The multimode nature of the waveguide means that it supports the low loss propagation of a range of higher order linearly polarized modes in addition to the fundamental EH11 mode. Figure 1 also shows a number of intensity profiles for representative waveguide modes, including EH11. Propagation is in the z-direction, with the inner waveguide walls located at the points –w/2 and +w/2 along the x and y axes respectively. It is clear that the EH11 mode has a quasi- Gaussian characteristic. The structure provides weak waveguiding, with minimal interaction (grazing incidence angles) of the lower order waveguide modes with the waveguide walls. Although the hollow waveguide is multimode in nature, when manufactured to be rigid and linear in a suitable substrate, the optical transmission properties of such waveguides are more controllable than those of multimode fibres.

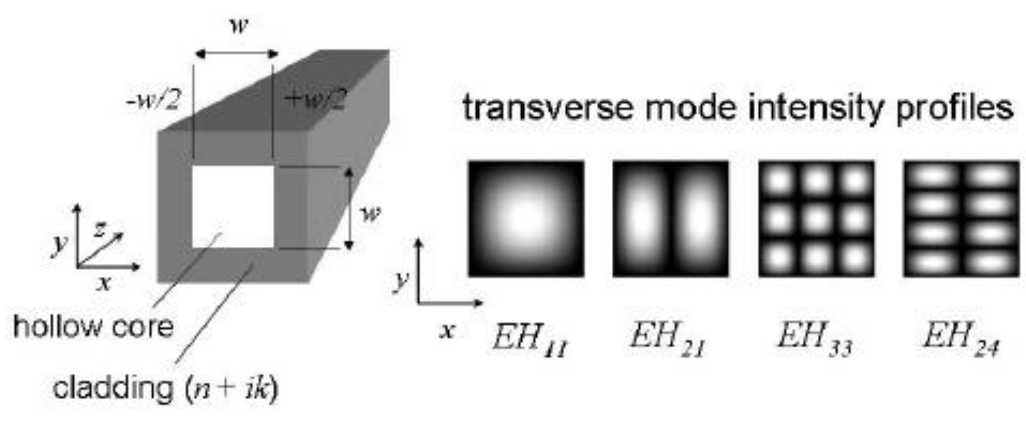


Figure 1. Schematic of square cross-section of width w.

For a full description of the theory of hollow waveguides the reader is referred to a number of publications [7],[8],[9]. Instead, two of the key issues are highlighted here. Firstly, Figure 2 illustrates that in order to achieve efficient fundamental mode coupling, the ratio of the $1/e^2$ TEM_{00} beam intensity waist diameter to hollow guide width, should be chosen to have a value of 0.703. Assuming a perfectly aligned input beam this value of waist diameter provides 98% power coupling from the TEM_{00} input beam to the fundamental EH_{11} waveguide mode, with ~1% of the power coupled into a range of higher order modes, and a further ~1% lost due to aperturing at the guide entrance.

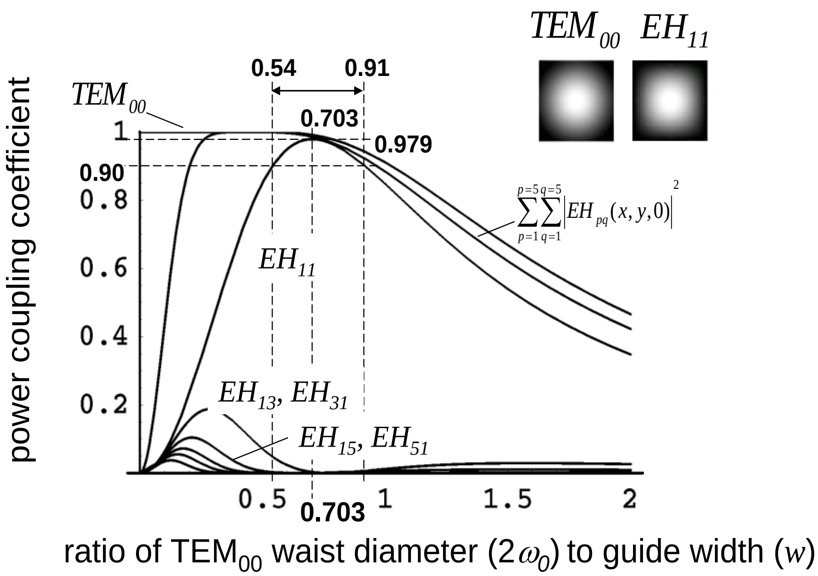


Figure 2. Hollow waveguide mode power coupling coefficients.

However, angular, lateral and axial misalignment of the input beam can also reduce the fundamental mode coupling with the result that appropriate alignment tolerances need to be defined and achieved in practice. A narrower waveguide width has an increased tolerance to angular misalignment, but a reduced tolerance to lateral misalignment.

As far as the choice of the hollow guide width is concerned, a further consideration is the attenuation that the fundamental mode will experience in practice when propagating in a given waveguide channel. Equation (1) is an analytical expression for the fundamental mode power transmission (in dBs).

$$T_{11_{dB}} = -4.34\frac{L\lambda^2}{w^3}\left[\mathrm{Re}\left(\frac{(n-ik)^2}{\left[(n-ik)^2 - 1\right]^{1/2}}\right) + \mathrm{Re}\left(\frac{1}{\left[(n-ik)^2 - 1\right]^{1/2}}\right)\right] \quad (1)$$

As dictated by the expression, the power transmission is dependent on the waveguide length, L, the waveguide width, w, the operational wavelength, λ, and the complex refractive index of the walls, n – ik, at the operational wavelength.

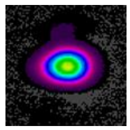
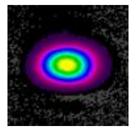
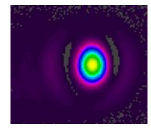
Both fibre-coupled and free-space input beams can be accommodated by the hollow waveguide, with efficient coupling to the EH_{11} waveguide mode if the mode-matching condition is met at the hollow waveguide entrance aperture.

3. LASER SOURCES

Three QCL devices were procured to support this work, two from Pranalytica (Santa Monica, California), and a third from Cascade Technologies (Stirling, UK). The key performance parameters of these lasers are summarised in Table 1.

The 1 W performance Pranalytica devices represented the highest power level commercially available at the time of procurement. The Cascade Technologies source demonstrated considerably lower power limited to 0.16 W. The similar wavelengths of one of the Pranalytica QCLs (Laser 1) and the Cascade Technologies source (Laser 3) allowed a demonstration of beam combining i.e. power scaling, in a common waveband using hollow waveguide technology. The lower electrical-to-optical conversion efficiency of the shorter wavelength sources (Lasers 1 and 3) compared to the longer wavelength source (Laser 2) is characteristic of QCL technology. All three QCLs generate linearly polarised output with a measured polarisation extinction ratio (PER) in excess of 50:1.

Table 1. Key performance parameters of the three QCL devices.

	Pranalytica		Cascade Technologies
Parameter	**Laser 1**	**Laser 2**	**Laser 3**
Power/W	1.04	1.03	0.16
E-O efficiency	3.6%	11.1%	3.7%
M^2	~1.0 (X) ~1.0 (Y)	~1.0 (X) ~1.0 (Y)	2.3 (X) 1.2 (Y)
Centre λ/μm	4.050	4.620	3.950
Far-field beam profile			

Both of the Pranalytica lasers were measured to generate diffraction-limited output beams (beam quality factor M^2 ~1), while the Cascade Technologies laser generated a more multi-mode output beam (as evidenced by the increased structure in the wings of the beam as shown in Table 1). The output beams of all three lasers demonstrated a considerable degree of astigmatism resulting in the beam profile being elliptical.

From Table 1 the three QCL sources generate output at the long wavelength end of the mid-IR waveband. Output at wavelengths close to the short end of the waveband (2 μm) is also required for the DIRCM application. QCL technology does not currently provide output at these shorter wavelengths. The most efficient solution is thulium fibre laser pumped Ho:YAG. A fourth laser source was built based on this technology, generating 2 W of linearly polarised cw output power at a wavelength of 2.1 μm. The output beam was diffraction-limited, with negligible astigmatism, i.e. the beam profile was highly circular both in the near-field and the far-field. High power (>30 W cw) operation of a similar Ho:YAG laser source has been reported previously [10].

4. HWBC OPTICAL CIRCUIT DESIGN

The beam combiner is based on a cascade of dichroic components integrated into alignment features in a Macor (machinable glass-ceramic, 46% silica by weight) substrate. Hollow waveguides, which take the form of square section channels in the surface of the substrate (together with a lid), are used to guide light from four separate input ports, each carrying a different input wavelength, to a common output port. The dichroic coatings on the components, and the properties of the HWBC optical circuit, were designed to be capable of combining the outputs from the Ho:YAG laser operating at 2.1 μm and three QCL sources at 3.95 μm, 4.05 μm and 4.6 μm, respectively. The detailed design of the HWBC optical circuit used here has been reported previously [11].

The optical schematic of the beam combiner layout is shown in Figure 3 including the polarisation states for each channel. The three dichroics (C1, C2 and C3) were specified and procured based on this design. Zinc selenide (ZnSe) was selected as the substrate material because it has excellent transmission properties in the mid-infrared, and the coefficient of thermal expansion (CTE) is well-matched to that of the Macor substrate. The transmission and/or reflection properties of the individual dichroics were measured at the wavelengths of interest using the four laser sources. An overall transmission of approximately 94% was measured for the optics path for the three QCL sources, while for the Ho:YAG laser at 2.1 μm the optics path loss was negligible (99.7% transmission). Note that these values are for dichroic performance only i.e. ignoring coupling and other waveguide losses.

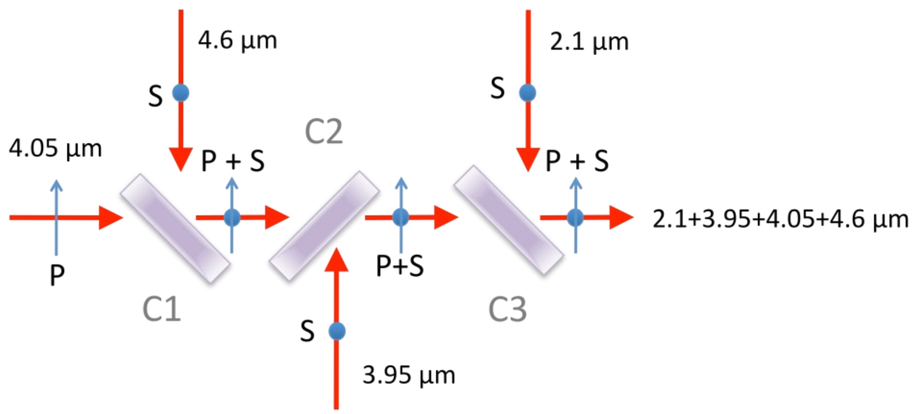


Figure 3. Schematic of the concept of using a cascade of dichroic components in order to combine the four input wavelengths at 2.1 µm, 3.95 µm, 4.05 µm and 4.6 µm, respectively. Note that the inputs at 2.1 µm, 3.95 µm and 4.6 µm, are chosen to be "s" polarized while the 4.05 µm input is chosen to be "p" polarized. These choices of input polarization, together with appropriate dichroic coatings, led to the most efficient optical design as far as maximizing the transmission of the individual wavelengths, and simplified the coating designs.

A solid CAD model of the HWBC optical circuit is shown in Figure 4 with the lid removed for clarity. A channel width of 1.2 mm was selected as the best compromise for minimising sensitivity to lateral and angular misalignments for the four wavelengths used.

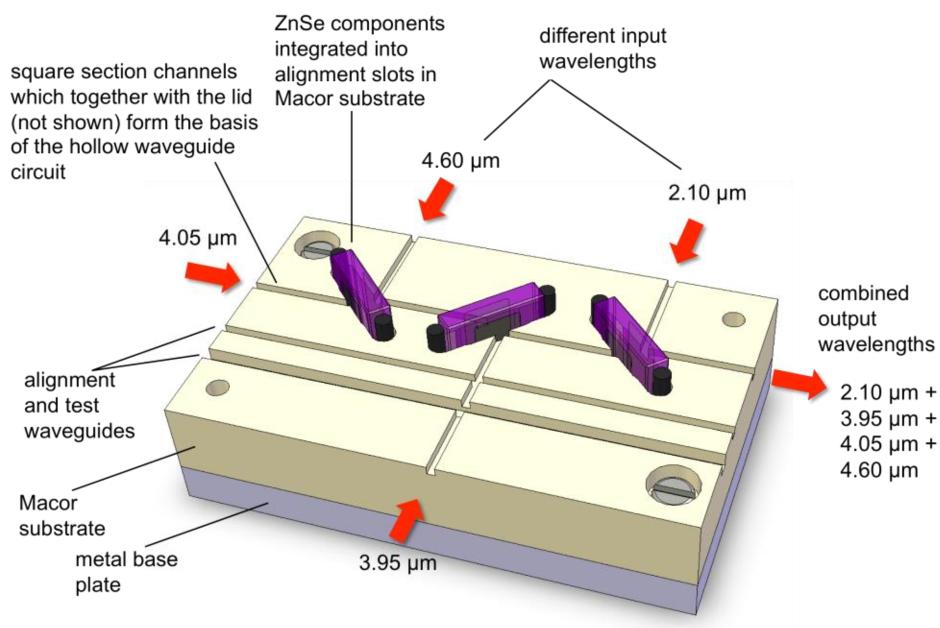


Figure 4. Schematic of the three dichroic components for the beam combiner integrated into alignment slots in a hollow waveguide integrated optic circuit created in the surface of a Macor (machineable glass-ceramic) substrate. The schematic illustrates the square cross-section channels, which together with a lid (not shown), form the square cross-section hollow waveguides which guide the light from the four different input ports to the common output port. The two additional waveguide channels, which as illustrated in the schematic are below the integrated components, are of different cross-sections and are for waveguide attenuation tests.

Two test guides were also included in the substrate of width 1.2 mm and 2.0 mm. These allowed each laser source to be individually tested in terms of transmission (combination of coupling efficiency and waveguide losses) and alignment sensitivity. The test guide performance was then used to baseline the performance of the HWBC optical circuit.

The actual manufactured beam combiner hardware is shown in Figure 5, again with the lid removed for clarity. Precision CNC milling techniques were used to create the waveguide channels and alignment slots in the Macor substrate.

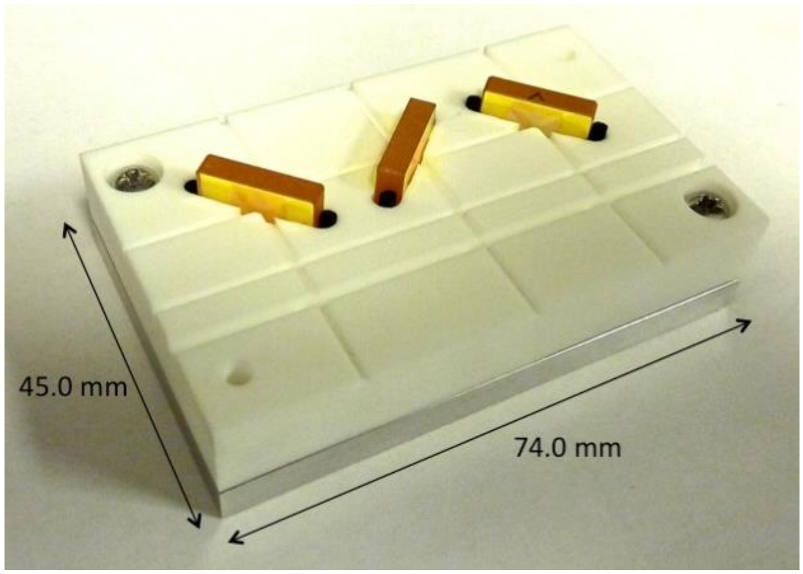


Figure 5. Manufactured HWBC optical circuit assembly (lid removed for clarity), with the overall dimensions.

The aluminium base plate, Macor machined substrate and ZnSe dichroic components are evident. The 15 mm square dichroics are a slide-fit into the alignment slots, which guarantees accurate location and alignment of the optics relative to each other and to the propagating beams.

There is considerable scope for further reduction in the dimensions of this compact hollow waveguide beam combiner. The width can be reduced by a factor of two simply by removing the test guides. Visual inspection of the machined hollow waveguide channels at grazing incidence reveals the high reflectivity achieved in this geometry using the Macor substrate.

5. HWBC OPTICAL CIRCUIT PERFORMANCE

The hollow waveguide beam combiner optical circuit hardware was integrated with the four laser sources on a 90 by 60 cm breadboard, as shown in Figure 6. For each laser source, a unique optical design was required to focus the free-space laser output beam to achieve the mode-matched condition i.e. a nominal waist diameter target of approximately 0.84 mm at the entrance to the 1.2 mm waveguide of each channel.

Due to the astigmatic nature of the output of the QCL sources, each design was optimised to achieve a mode-matched beam waist that was as near circular as possible at the entrance to the hollow waveguide. These mode-matching optics took the form of a simple lens pair. Each lens was mounted on an XYZ translation stage in order to provide steering of the beam into the corresponding hollow waveguide channel as well as control of the beam size in order to provide mode-matching into this hollow waveguide channel. Additionally, a half- waveplate ($\lambda/2$ at 4 µm) was incorporated into each of the beam paths of the 3.95 µm and 4.05 µm sources to rotate the polarisation by 90º in order to achieve the correct polarisation state (s and p respectively) for coupling into the HWBC optical circuit.

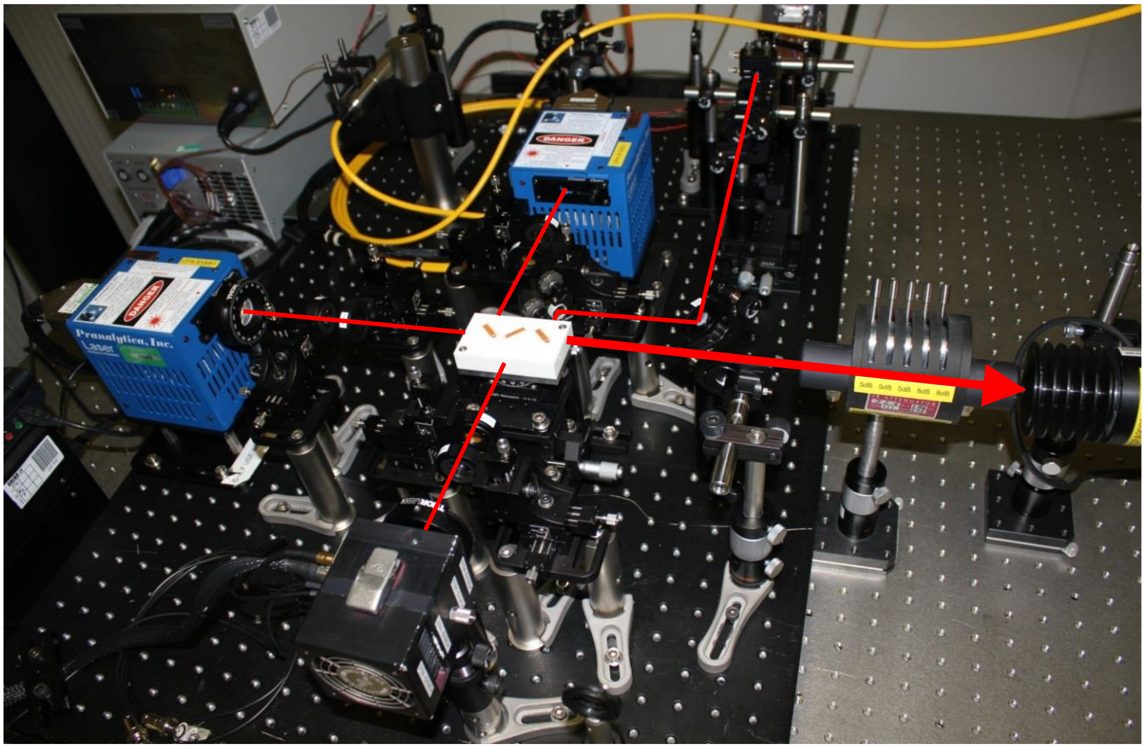
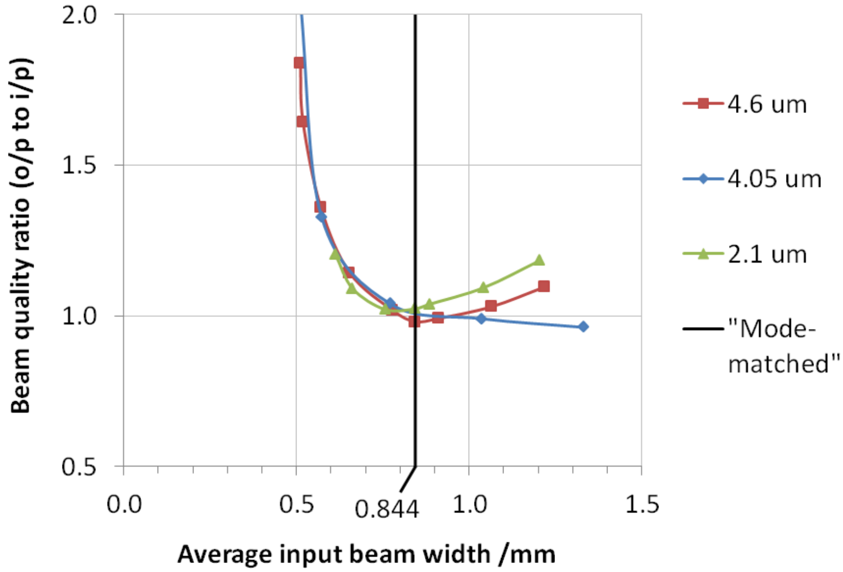


Figure 6. Photograph of the breadboard integration of the hollow waveguide beam combiner with the four laser sources.

The initial assessment of the HWBC optical circuit was conducted by coupling the output from each laser source into the 1.2 mm test waveguide and comparing the output to the input in order to evaluate the transmission of the waveguide and the effect on the beam quality. In each case, the input beam was carefully aligned to the waveguide axis to achieve the brightest, most symmetrical output beam profiles in both the near- and the far-field. These tests were undertaken using the diffraction-limited beam quality sources (Pranalytica Lasers 1 and 2, plus the Ho:YAG laser). With input beam diameters as close to the mode-matched condition as possible, high waveguide transmission values of 98.3%, 95.3% and 95.5% were obtained at 2.1 µm (Ho:YAG), 4.05 µm (Pranalytica Laser 1) and 4.6 µm (Pranalytica Laser 2) respectively. The similar transmission values for the two Pranalytica QCLs reflect the similar output beam characteristics of these two devices. The higher transmission obtained at 2.1 µm was attributed to the better circularity of this source at the input to the waveguide. In this case optimum coupling into the EH11 fundamental waveguide mode was achieved. The measured transmission of 98.3% implies that the test waveguide had negligible transmission losses at 2.1 µm.

The beam quality of the beams exiting the test waveguide was measured and compared to the corresponding beam quality of the input beams. The ratio of output to input beam quality versus the average input beam width is plotted for the three lasers in Figure 7.

As expected any degradation in output beam quality was minimised when the mode-matching criterion was met (input beam width 0.84 mm). At 2.1 µm there was no measured degradation in beam quality and the output beam remained diffraction-limited. At both 4.05 µm and 4.6 µm a slight degradation in beam quality was measured (factors of 1.1 and 1.2 respectively) from the input diffraction-limited beams. This is attributed to non-ideal mode-matching due to the elliptical nature of the QCL beams introducing higher order mode content to the beam as it propagated along the test waveguide. The higher order mode content experiences higher propagation losses, resulting in an overall reduction in transmission. From Figure 7 the beam quality is degraded more rapidly if the input beam width is smaller than the mode-matched case. This is because the resultant propagating beam in the waveguide has a larger divergence which provides coupling into higher order modes. An input beam width larger than the mode-matched case will excite higher order modes at the waveguide entrance and cause greater aperturing.



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The sensitivity to misalignment was also assessed using the 1.2 mm test waveguide. A lateral misalignment of the waveguide relative to the beam in the range 0.25-0.30 mm was required in order to produce a 5% decrease in transmitted power for all three lasers tested. The corresponding rate of shift in the far-field centroid (as a percentage of the nominal divergence) with lateral misalignment was 77%/mm for the two Pranalytica QCL devices, and 17%/mm for the Ho:YAG laser. An angular misalignment of the input beam relative to the waveguide of 6 mrad was required in order to introduce a 5% decrease in transmitted power for the Ho:YAG laser, with a corresponding misalignment of 9 mrad for the QCL devices. The corresponding rate of shift in the far-field centroid (as a percentage of the nominal divergence) with angular misalignment was 0.9%/mrad for the two QCL devices, and 0.2%/mrad for the Ho:YAG laser. The misalignments (both lateral and angular) required to introduce a 5% power loss are very large compared to the misalignments typically introduced by operation over a wide temperature range, or in a harsh vibration environment. Therefore the HWBC optical circuit can be considered as insensitive to misalignment.

Each of the four lasers in turn was coupled into the appropriate channel in the HWBC optical circuit (as defined by the layout in Figure 3). By comparing the output power from each channel of the HWBC optical circuit against the input power, the transmissions of each wavelength channel were calculated to be 99% at 2.1 µm and 89% and 4.05 µm and 4.6 µm. An estimate of the coupling efficiency associated with the each wavelength channel of the HWBC was obtained by dividing these values by the channel transmission values associated with the laser-based measurements of the dichroic optics discussed in the previous section. Using this method, the coupling efficiencies are calculated to be around 99%, 95% and 94% at 2.1 µm, 4.05 µm and 4.6 µm respectively. These values are in reasonably good agreement with those obtained using the test waveguide (98.3%, 95.3% and 95.5% respectively) within experimental error. This confirms that the mechanical tolerances of the HWBC associated with the mounting and registration of the dichroic optics do not introduce any significant additional losses in the beam combining channel, when compared to the (straight-through) test waveguide. The measurements indicate the waveguide propagation losses at each wavelength can be considered negligible.

Finally the Cascade Technologies QCL was integrated with the HWBC optical circuit. An overall waveguide transmission of 75% was measured, yielding a coupling efficiency of 80% (given the 94% transmission of the dichroic optics previously measured). This value is significantly lower than the values of 95–98% obtained for the other lasers, and reflects the significantly poorer beam quality and astigmatism of the Cascade Technologies QCL. A small improvement in the beam quality of the output form the HWBC optical circuit provided evidence that the waveguide was acting as a mode-filter, removing some higher-order mode-content in the beam.

A combined maximum output power of 4.2 W was measured from the HWBC optical circuit using the four laser sources (with a standard deviation of the mean of <0.1% over a 30 second firing period). The overall transmission of the HWBC optical circuit, weighted by the laser power at each wavelength, is 93%.

The far-field beam of the combined output of the HWBC optical circuit, with all the sources operating at full power, is shown in Figure 8. The combined full-angle far-field beam divergence was measured to be 6.4 mrad in a highly circular near diffraction-limited beam. The boresight of each source relative to the mean boresight position of the combined beam was measured to be 20 µrad (0.3% of the divergence of the combined beam).

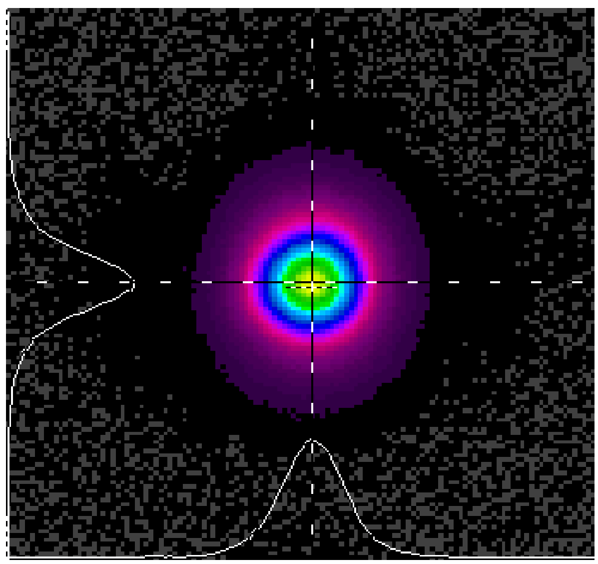

Figure 8. Far-field beam profile of the combined output of the HWBC optical circuit.

This confirms that the HWBC optical circuit guarantees common boresight of the individual input beams at the exit aperture of the optical circuit.

6. CONCLUSIONS

A compact, rugged, beam combiner for combining four wavelengths covering the wavelength range 2.1 µm to 4.6 µm has been designed, manufactured and characterised. The beam combiner consisted of a series of dichroic components integrated into a hollow optical waveguide circuit for confining, combining and directing the optical beams from four discrete waveguide input ports to a common output port. By coupling each wavelength into the fundamental mode of the waveguide circuit, common boresight of the combined wavelengths was achieved. Precision CNC milling techniques have been used to manufacture the hollow waveguide circuit and the alignment slots for the dichroic components, in a common Macor substrate. The approach leads to easy assembly without the need for individual component alignment mounts or sophisticated alignment procedures.

4.2 W of combined output power from three QCL devices and a thulium fibre laser pumped Ho:YAG laser was demonstrated, with an overall transmission for the HWBC optical circuit of 93%. Propagation losses in the waveguide sections were negligible. The major contributor to the overall loss was the performance of the dichroic optics for the near diffraction-limited beams used here.

The four wavelengths were co-boresighted to better than 20 μrad in the common output beam exiting the HWBC optical circuit.

The performance of the HWBC optical circuit was measured to be insensitive to lateral and angular misalignments typical for operation over a wide temperature range, or in a harsh vibration environment.

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