Abstract. Lasers and amplifiers emitting 2 µm single-frequency pulses are used for spectroscopy, remote sensing, and defense applications. The laser sources group at the CSIR National Laser Centre has developed a number of 2 µm lasers and amplifiers over the course of five years. We report on three of these, all of which achieved record breaking output energies. To generate the high energy 2 µm pulses, we developed a 70 mJ single-frequency, Q-switched Ho:YLF ring MOPA. Both the ring laser and pre-amplifier were pumped by a single commercial 80 W, 1940 nm, Tm:fibre laser from IPG. The seed laser system delivered up to 73 mJ per pulse at 50 Hz, with a pulse duration of ~365 ns in a diffraction limited beam. This system set two world records: it delivered the highest energy from a Ho doped laser, pumped with one Tm:fibre laser, and it was also the highest single-frequency singly-doped Ho:YLF laser. In order to scale these pulse energies even further, we developed a Tm:YLF pumped slab amplifier system. Amplified single-frequency pulses of up to 210 mJ were generated from a 43 mm long Brewster cut Ho:YLF and a 20 mm long Ho:LuLF slab crystal. However, numerical simulations indicated that longer Ho doped crystals between 80 to 120 mm in length would perform significantly better. A new Ho:YLF slab amplifier was therefore built which consisted of two 50 mm long crystals placed close together in series in a double seed pass configuration. This amplifier delivered >330 mJ of single-frequency pulses and a small signal gain in excess of 40. This is the highest reported single-frequency 2 µm energy from a Ho:YLF slab MOPA system. The high-energy 2 µm pulses were then used to pump a 4 µm molecular HBr MOPA, which will also be reported at this conference.

1. Introduction
Systems emitting 2 µm single-frequency pulses can be used for remote sensing, spectroscopy and defense applications. This paper reports, in chronological order, on three different amplifier systems developed at the National Laser Centre in Pretoria, South Africa. The first is a Ho:YLF rod pre-amplifier which amplified 26 mJ of a single frequency output from a Ho:YLF ring laser to 73 mJ. The second is a Ho:YLF & Ho:LuLF slab power amplifier that further amplified the output of the pre-amplifier up to 210 mJ. This amplifier was then significantly modified to finally scale the pulse energy up to 330 mJ. The paper is divided into three sections, each describing a specific amplifier.
2. Ho:YLF rod pre-amplifier \[1\]

A Ho:YLF ring oscillator producing \(\sim 30\) mJ of single frequency, 2064 nm pulses \[1\] was used as a master seed oscillator and was pumped by a single commercial 80 W, 1940 nm, Tm: fibre laser from the company IPG Photonics. Both the master oscillator and pre-amplifier are illustrated in Figure 1. It was estimated that the best compromise between oscillator performance and damage threshold would be achieved with a pump and laser mode radius of 1 mm in the 40 mm long, 0.5% doped Ho:YLF oscillator crystal (which was also the smallest mode size in the oscillator). The ring oscillator was designed to have a length of 2.4 m which produced long Q-switched pulses. Injection seeding from a single-frequency diode from TOPTICA was achieved through the first-order diffracted beam of a 27 MHz AOM.

![Figure 1. The Ho:YLF ring master oscillator and pre-amplifier system.](image)

The traditional approach for a fibre-laser-pumped Ho:YLF laser amplifier system is to split the unpolarized beam from a Tm-doped fibre laser with a polarizing beam splitter to utilize the two polarized beams to pump an oscillator and an amplifier. In a novel approach, the full power of the unpolarized pump beam was used to pump a relatively short Ho:YLF crystal in the ring oscillator, which absorb roughly half of the pump light. The transmitted pump power, which is relatively well polarized, was then used to pump two rod Ho:YLF amplifier crystals. For optimum pump absorption, the oscillator and amplifier Ho:YLF crystals were orientated with their \(c\)-axis perpendicular to each other (\(c\)-axis horizontal in the oscillator crystal and vertical in the amplifier crystal). The oscillator operates on the \(\sigma\)-polarization, which has a weak thermal lens (resulting in higher quality beams) but also has a lower gain cross section. The single-pass amplification takes place on the \(\pi\)-polarization with its higher gain cross section but also stronger thermal lens. The pump was reflected back through the system for a double pass and the output of the ring oscillator was shaped and aligned through the two amplifier crystals before being steered out of the system.
Figure 2. The performance of the Ho:YLF ring master oscillator and pre-amplifier system as a function of Pulse Repetition Frequency. The insert shows the near perfect beam quality.

The Ho:YLF pre-amplifier amplified the 26 mJ pulses from the master ring oscillator up to 73 mJ per pulse at 50 Hz, with a pulse duration of ~365 ns, in a diffraction limited beam, of which of 69 mJ was available for seeding additional power amplifiers. Figure 2 shows the performance of the system versus pulse repetition frequency as well as the near perfect beam quality of the system. This set two world records: it delivered the highest energy from a Ho doped laser, pumped with one Tm:fibre laser, and it was also the highest single-frequency singly-doped Ho:YLF laser.

3. Ho:YLF & Ho:LuLF slab power amplifier [2]
The output of the oscillator/pre-amplifier system was then further amplified by means of a Ho-doped slab power amplifier [2]. This is illustrated in the optical layout given in Figure 3. The amplifier was end-pumped with a 181 W Tm:YLF slab laser [3] (“Pump Laser” in Figure 3) which was forced to operate on the \( \pi \)-polarisation which oscillated at 1890 nm. The elongated pump beam from the Tm:YLF slab laser was first collimated with an \( f = 105 \) mm spherical lens placed directly after its output-coupler. It was then first focused with an \( f = 60 \) mm spherical lens into a \( 10\times2\times20 \) mm\(^3\), \((c\times\alpha\times\alpha)\) \( a \)-cut Ho:LuLF crystal and then into a \( 10\times2\times43 \) mm\(^3\), \((c\times\alpha\times\alpha)\) \( a \)-cut Brewster faced Ho:YLF crystal (50 mm from tip to tip). The pump beam was also horizontally polarized parallel to the \( c \)-axes of two Ho doped crystals.

The diffraction limited seed beam was shaped with three cylindrical lenses to be collimated in the horizontal direction and focused in the vertical direction (\( w_{0x} = 2.9 \) mm & \( w_{0y} = 0.49 \) mm), while the crystals remained inside the Rayleigh range of the focus and also matched the pump sizes in the crystals fairly well so that good extraction efficiency could be achieved. The seed beam was \( \pi \)-polarised along the \( c \)-axes of the two Ho-doped crystals, resulting in a higher gain (due to higher emission cross-sections of their respective \( \pi \)-polarisations) but also experienced stronger thermal lensing effects.
Figure 3. Optical layout of the Ho:YLF & Ho:LuLF slab power amplifier. At the full incident 1.9 µm pump power of 181 W, the amplifier was optimized to deliver pulse energies of up to 210 mJ from 69 mJ seed pulses at a pulse repetition rate of 50 Hz, resulting in a gain of 3.2 with 70 W of the pump light absorbed. Figure 4(a) illustrates the amplified energy and amplifier gain as functions of absorbed pump power and shows that the increases in output energy and gain were almost linear. The amplifier output energy (at 50 Hz and full pump power) as a function of incident seed energy from the single-frequency ring laser system is plotted in Fig. 4 (b). A range of seed energies were obtained by inserting different partial reflectors with reflectivities ranging from 33% to 99% into the path of the seed laser beam before it entered the amplifier. The amplified energy varied from 29.6 mJ for a seed energy of 6.4 mJ (gain of 4.6) to 210 mJ for a seed energy of 68.8 mJ (gain of 3.05). This set a world record for the highest energy output of a single frequency single-doped Ho slab amplifier system. However, numerical simulations indicated that longer Ho doped crystals between 80 to 120 mm in length would perform significantly better.

Figure 4. The Ho:YLF & Ho:LuLF slab amplifier output energy and gain versus absorbed 1.9 µm Tm:YLF pump power (a) and seed energy (b).
4. 300 mJ 100 mm Ho:YLF slab amplifier [4]

The slab power amplifier discussed in the previous section was then significantly modified. The Ho:LuLF and Brewster-cut Ho:YLF amplifier crystals were replaced with two 10 x 2 x 50 mm (c x a x a) Ho:YLF slab crystals placed close together in series (Figure 5) [4]. The pump beam was also modified to fit into the two longer gain media by adding an f = 250 mm horizontal cylindrical lens in the pump beam and adjusting the position of the f = 60 mm pump lens to shift the focus to the middle of the two Ho:YLF crystals. The polarization of the seed beam was also changed so that it was amplified on the slightly weaker gain σ-polarization of Ho:YLF (along the a-axis) because the strong thermal lens associated with the π-polarization caused severe distortion of the beam due to possible clipping within the crystal. The seed laser was then double passed through the crystals (as opposed to the single pass setup of the Ho:LuLF/Ho:YLF amplifier) by reflecting it of a 2 µm 0° high reflector which also had a high transmission from the pump wavelength of 1.9 µm (M3 in Figure 5). The amplified beam was then separated from the seed beam. Optical feedback, back into the master ring oscillator, was prevented by tilting the double pass mirror (M3 in Figure 5) at a slight angle. However, the amplified beam still destabilized the master ring oscillator at high output energies. To compensate for this, an optical isolator had to be inserted at the ring oscillator exit (between the oscillator and pre-amplifier in Figure 1) which decreased the available seed energy from ~69 mJ to 57 mJ.

Figure 5. Optical layout of the 2×50 mm Ho:YLF slab power amplifier.

The amplified energy was measured at a 50 Hz repetition frequency as a function of the 1.9 µm Tm:YLF pump power. The result can be seen in Figure 6 (a). At maximum pump power the output energy increased to ~325 mJ (at 50 Hz) while the gain increased to ~5.7. At the slightly lower pulse repetition frequency of 30 Hz the amplifier output energy increased to a record breaking 333 mJ. Figure 6 (b) shows the amplifier performance as a function of seed energy. A small signal gain in
excess of 40 was measured which was an order of magnitude improvement over the previous Ho:LuLF/Ho:YLF power amplifier. This indicated that the beam size and crystal length were optimally chosen. This system therefore broke the group’s previous world record for the highest energy output of a single frequency single-doped Ho slab amplifier system. The high-energy 2 µm pulses were ultimately used to pump a 4 µm molecular HBr MOPA [5].

Figure 6. Optical layout of the Ho:YLF & Ho:LuLF slab amplifier output energy and gain versus absorbed 1.9 µm Tm:YLF pump power (a) and seed energy (b).

5. Summary and Conclusions
Three different amplifier systems were reported on. Each significantly scaled single frequency 2064 nm pulses to higher energies. The optimised solution used two 50 mm Ho:YLF crystals which scaled the output to a record breaking ~325 mJ output at 50 Hz and 333 mJ at 30 Hz.

References