Lasers:
Academic and Company Collaboration Yields Surprising Result

Introduction

The 1960s was a truly impressive period of development as far as lasers and the understanding of their operation was concerned. The decade saw a rapid growth in research papers including a clutch of key ones that covered the underpinning physics eg the fundamentals of Q-switching and mode-locking, the role of resonator modes in stable and unstable cavities, amplifier performance and saturation, etc. Many of these papers have stood the test of time and today, almost half a century on, they remain as useful to the laser engineer as in those early days - they are the cornerstone of every laser handbook. Despite the huge growth in laser research since those early days, uncovering some useful fundamental laser physics that might have come to light in the interim is not that common. However, this we feel is the case with work reported in our recent paper in Optics Communications(1).

Staff at AOT and the Department of Physics at Hull University have been working together for sometime on a programme of work to optimise Q-switched MOPA (Master Oscillator and Power Amplifier) performance for nanosecond pulses in diode-pumped SSL systems. The work has benefited from the commercial imperatives of AOT (to get results and viable solutions for customers), the commitment and academic rigour of the research group at Hull, and the freedom to apply time to the problem afforded by generous financial support from the Royal Commission for the Exhibition of 1851 to one of us (SP) in the form of a 3yr Industrial Fellowship.

Research Programme

The SSLs involved in our study typically operate at kHz rates with oscillators producing pulses to ~ 50kW, but at sub-watt average power. For many applications, amplification is required to raise the average power into the multi-watt range. This is most simply done by using a double-pass amplifier tilted at a small angle to the incoming beam, as indicated schematically in Fig (1) below.

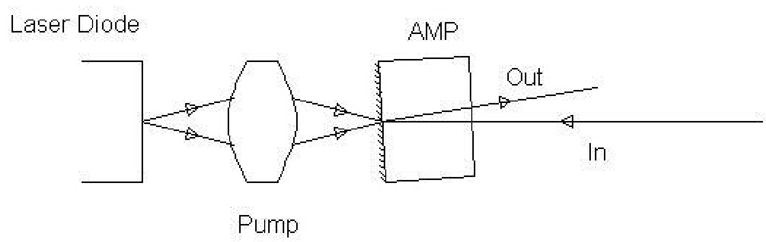

Fig (1) Simple arrangement for double-pass operation of an end-pumped SSL amplifier

The approach in Fig (1) can allow amplification of a high quality beam, and with good extraction of the amplifier stored energy in the case of an input fluence of the order of the saturation energy density. This is not a new arrangement, but is a set-up of growing importance for miniature amplifiers.

In 1963, Franz and Nodvik[2] published their well-know paper on amplifier performance under large input signal (saturation) conditions. This includes the simple and elegant result (reproduced below) that links gain to key amplifier parameters.

$$E_{out} = E_s \ln\left[1 + \left(\exp\left(\frac{E_{in}}{E_s}\right) - 1\right)\exp(\sigma N_0)\right] \qquad (1)$$

Equation (1) is that derived by Franz and Nodvik in 1963. For a beam passing through an amplifier, it links output fluence E_{out} to saturation fluence E_s, input fluence E_{in}, stimulated emission cross-section σ, and the initial length-integrated inversion N_o.

The expression derived by Franz and Nodvik is a powerful tool widely used for helping to predict amplifier performance. However, where there are counter-propagating beams that overlap, as in the double-pass arrangement in Fig (1), no comparable analytical expression has been available. Hitherto, in such cases, numerical methods have had to be used to model amplifier performance.

Our work has investigated the situation where counter-propagating beams pass through the amplifier and are amplified at the same time, each extracting some of the stored energy. It is for this type of arrangement we report useful progress. We were surprised to find that equation (1) can be generalised, and for M-passes of the amplifier has the form:-

$$E_{out} = \left(\frac{E_s}{M}\right)\ln\left[1 + \left(\exp\left(\frac{ME_{in}}{E_s}\right) - 1\right)\exp(M\sigma N_0)\right] \qquad (2)$$

We have found that this new expression is a useful tool, not only to help model the double-pass (M = 2) amplifier performance in Fig (1), but also in the case of multi-pass performance ie M > 2. The latter can be important in situations where the oscillator input does not heavily saturate the amplifier in a single or double pass. ie the input fluence to the amplifier is low and/or the amplifier saturation fluence is high (eg where Nd:YAG or Nd:Glass is used for the amplifier).

Multi-pass (M > 2) amplifiers are less widely reported than double-pass (M = 2) configurations. However, some simple and practical arrangements are possible, and two are shown in Figure (2) below. One of these has M = 4 and the other M = 8

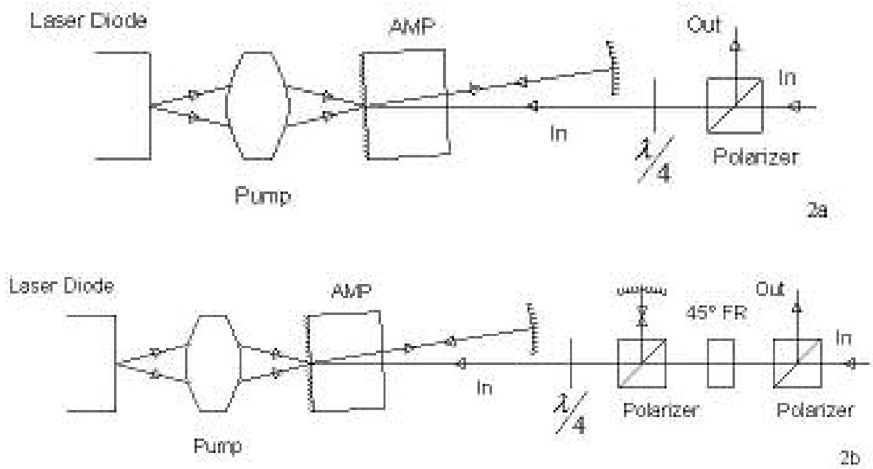

Fig (2). Two simple arrangements that provide multi-pass (M > 2) amplification. In Fig (2a) M = 4, and in Fig (2b) M = 8.

As an example of the application of Equation (2), we have considered the case of a short Nd:YAG amplifier end-pumped in a ~ 1mm diameter spot by a ~ 75W peak power diode bar with a fibre pigtail. Figure (3) indicates the maximum amplifier performance (extraction efficiency) for different oscillator input pulse energies in the range 1μJ to 1mJ.

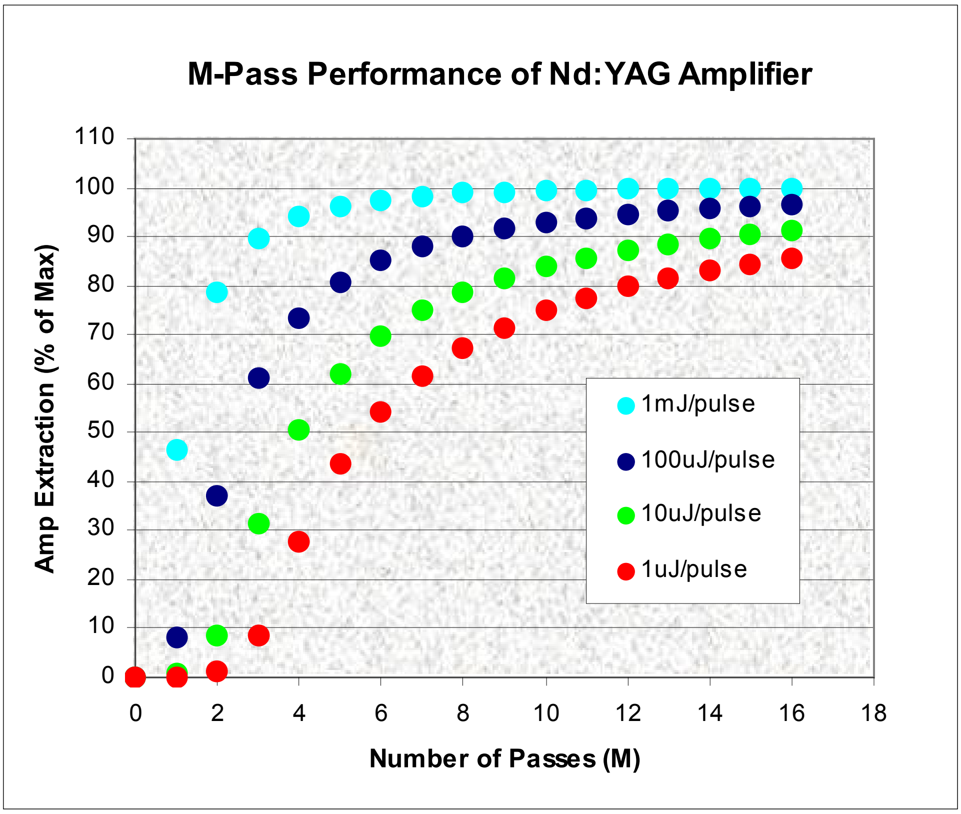

Fig (3) Multi-pass Nd:YAG amplifier with beam overlap and input pulses of 1μJ to 1mJ at low rep-rate

The data presented in this way can be used to help make early design decision. For this particular example, it is evident that with an input of ~ 1mJ/pulse a double-pass amplifier arrangement would allow good stored energy extraction (ie ~ 80%).

However, if the input from the oscillator was in the region of ~ 100μJ/pulse, a 4-pass arrangement would be required for good efficiency, and for ~ 10μJ/pulse 8-passes. In the limit of a low input pulse energy (ie < 1μJ/pulse), the figure points to the need to consider the possibility of a regenerative amplifier arrangement instead of a multi-pass one to efficiently extract amplifier stored energy.

Summary

We find that the availability of this generalised analytical expression for multi-pass amplifier performance provides a very useful aid in laser system design, and hope and expect that others will too. We have found it rewarding to discover a simple result that (apparently) has remained hidden for so long. In no small part our progress has been due to a close and effective academic/industry partnership coupled with generous financial support for the work.

(1) S Pearce, CLM Ireland and PE Dyer, 'Simplified Analysis of Double-Pass Amplification with Pulse Overlap and Application to Nd:YVO_4 Laser', Opt Comm (in the press)

(2) LM Franz and JS Nodvik, 'Theory of Pulse Propagation in a Laser Amplifier', J Appl Phys, Vol 34, p2346, (1963)