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Multiple-Beam Pulse Shaping and Preamplification

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Introduction

Glass fusion laser systems typically use a master oscillator-power amplifier (MOPA) architecture, where control of the optical pulse temporal and spatial parameters is accomplished mainly in the master oscillator and low power optics. The pulses from this low power "front end" are amplified in the power amplifier, which modifies the pulse shape temporally and spatially. Nonlinear frequency conversion crystals following the amplifier further change the pulse before it reaches the target. To effectively control the optical pulse on target for different types of experiments, and compensate for nonlinearity in the preceding optics, the front end system must be versatile enough to easily control many pulse parameters over a large range. The front end pulse generation system described in this article represents a new approach to this problem.

The proposed National Ignition Facility (NIF) has 192 beamlines, each of which requires an input pulse of up to 12 Joules in around 4 ns equivalent square pulse length. Considerations of laser architecture for supplying each of these beamlines from a central oscillator system were crucial in the design of the front end. Previous lasers have used bulk optics to split a single oscillator signal and transport beams to multiple amplifier chains. A key idea in the current design is to replace bulk optic transport with fibers, eliminating large opto-mechanical subsystems. Another important concept is convenient pulse forming using low voltage integrated optic modulators. Previous systems have used high voltage devices for pulse forming, which lack flexibility and reliability. The integrated optic and fiber optic concepts resulted in the current pulse generation designs for NIF. An important advantage is that each of the beamlines can have an independently controlled temporal pulse shape, which provides for precise balance of instantaneous power on target. This is made possible by the high reliability and low cost of the integrated optic pulse forming systems.

The overall NIF front end system is composed of five major subsystems: the master oscillator, modulator, fiber distribution, and preamplifier. The first two subsystems are located in the master oscillator room (MOR). The last two subsystems are located in the two laser bays with the fiber distribution subsystem providing the link between .
In addition to its basic signal generation functions described above, the MOR must provide accurate timing signals to other systems in the laser that must be precisely synchronized.

Figure 1 gives an overall view of the front end subsystems. The following descriptions track the optical signal path through the front end, and outline the functions of associated subsystems.

Master Oscillator Subsystem

The master oscillator system provides light inputs to the 192 pulse shaping modulators, in the form of 2.5W, 30ns pulses. Four oscillators provide four different wavelengths separated by 10 angstroms, near 1,053nm, and each wavelength is amplified, split, and sent to 48 of the 192 outputs. Phase modulation is applied before splitting, since the same bandwidth will suffice for all beams. The oscillator is shown with the amplification and splitting hardware in figure 2.

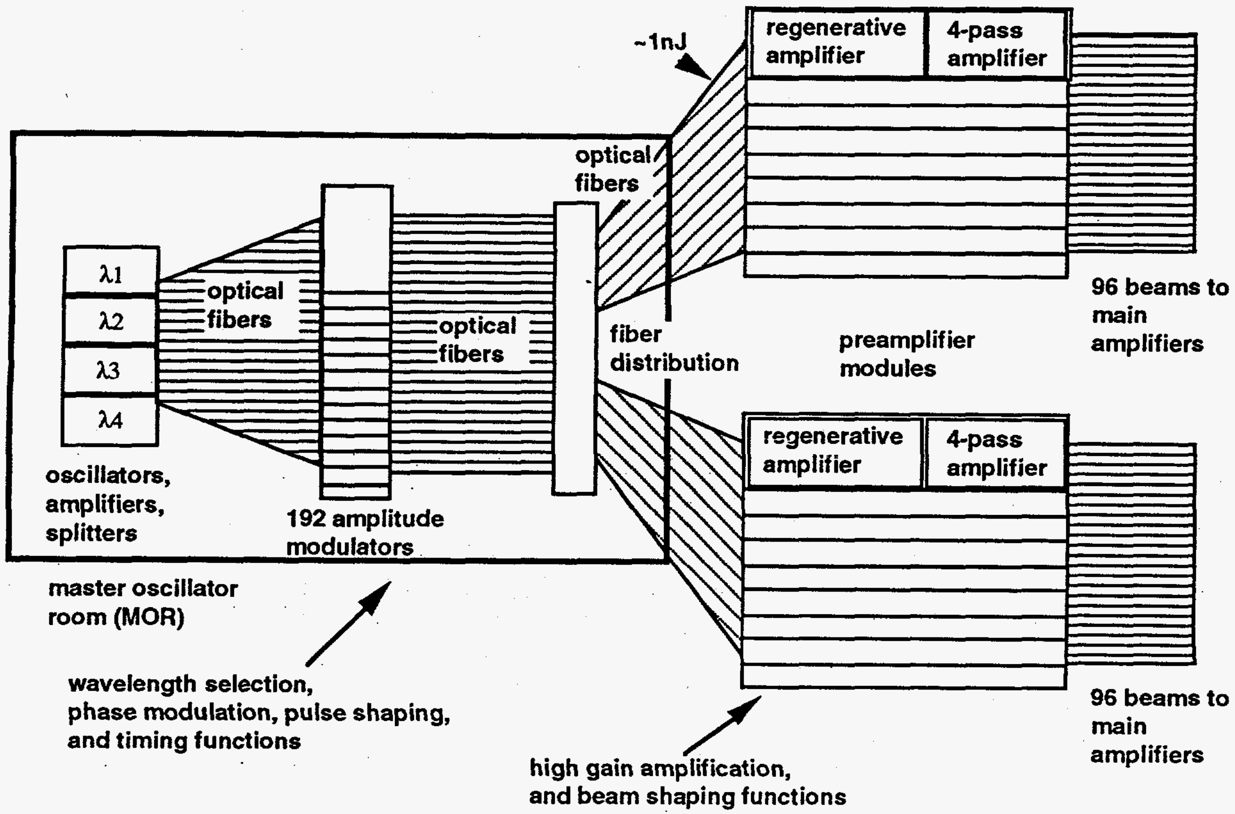

Figure 1. The overall front end architecture.

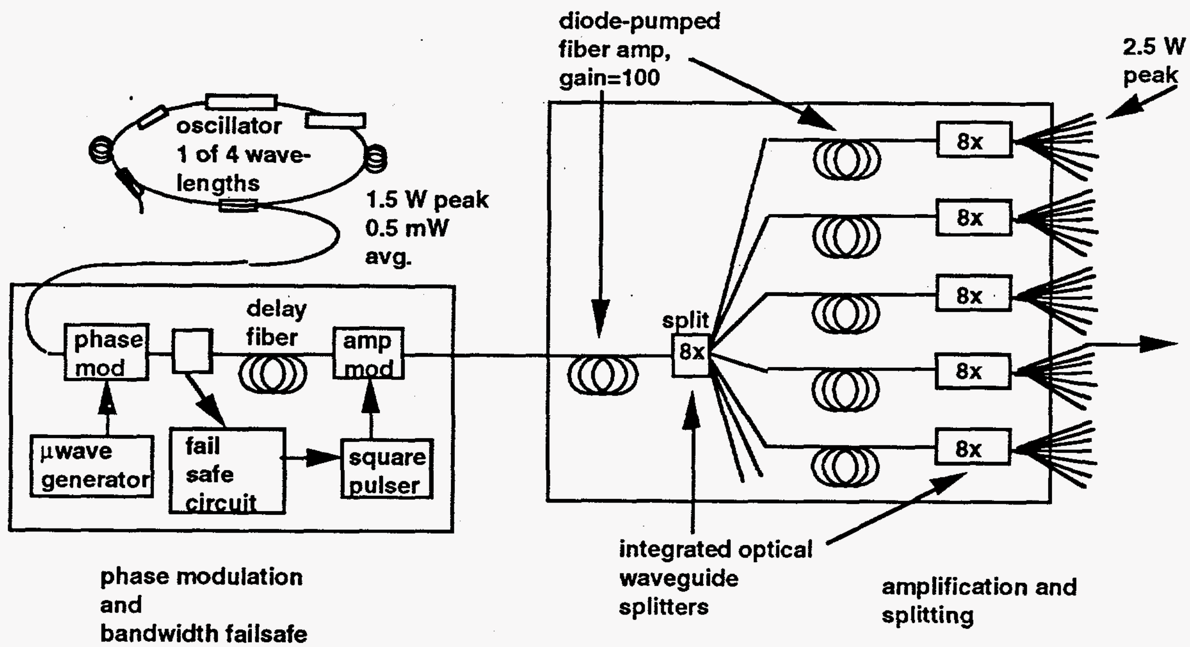

Figure 2. The master oscillator subsystem.

Both the oscillator and the subsequent amplifiers have been designed with ytterbium-doped silicate fiber as the gain medium. This material has a broad gain bandwidth which covers the spectral region of interest. These fibers have a smaller stimulated emission cross section and longer fluorescence lifetime than neodymium in silicate glass (1), resulting in desirable attributes of higher saturation fluence and lower amplified spontaneous emission. Experiments have shown that Yb fiber lasers can operate efficiently when pumped with diode lasers, and can be Q-switched to produce energetic pulses (2).

The oscillator will be a diode-pumped, Q-switched, single-longitudinal-mode-fiber ring laser. Single mode operation is produced by wavelength selection techniques employed in erbium-doped fiber lasers used in communications (3). A fiber Fabry-Perot etalon selects the cavity mode, while a birefringent filter selects modes of the etalon, resulting in one cavity mode having the highest gain.

The laser is Q-switched to produce adequate output power and to control cavity dynamics such as relaxation oscillations. The Q-switch is an integrated optical waveguide modulator, similar to the extra cavity modulators.

Phase modulation

A 100 ns long pulse of light from the Q-switched oscillator passes through an integrated optic, lithium niobate waveguide phase modulator where the single frequency is spread into several, relatively equal amplitude sidebands for suppression of Stimulated Brillouin Scattering (SBS)(4). The applied modulation is synchronized with the amplitude modulation applied in the subsequent pulse shaper, so that the frequency content of a short pulse will be constant from shot to shot, rather than having a random number of FM cycles in its duration.

Following the phase modulator is the waveguide chopper modulator, driven by a 30 ns square pulse, which defines the duration of the output of the oscillator subsystem.

Amplification and splitting

To distribute the light to the modulators, the oscillator pulse is amplified and split in two stages. Each fiber amplifier in the system has a gain of 100 and is pumped by a diode laser emitting at 910 nm. Pump light is coupled into the amplifying fiber by a wavelength selective coupler. The fiber amplifier design is similar to that used in commercial fiber amplifiers. In order not to burden the dynamic range of the modulators, the fiber amplifiers are run well below saturation to avoid excessive pulse shape distortion.

An integrated optical 1-by-8 splitter, consisting of a tree of Y-branches, splits the pulse while maintaining polarization. Polarization maintaining (PM) fiber is used to ensure insensitivity to temperature effects. The components in the signal line, including the splitters, are specified to maintain polarization extinction better than 1%.

Amplitude Modulator Subsystem

The NIF amplitude modulator system must provide temporally shaped optical pulses of 100ps to 20ns duration, with greater than 50dB prepulse extinction, and 5ps timing resolution. These specifications are based on experience with the Beamlet demonstration system. The main differences for NIF are digital programmability, and integration of the pulse shaping system into a modular package.

A typical optical pulse shape required at the preamplifier module output (i.e. the transport spatial filter injection point) is shown in figure 3. For the largest injection energy, the worst case preamplifier module saturation is about 2.4, making the peak-to-foot optical contrast ratio at the modulators about 280. The pulse shaping system is capable of a 500:1 optical contrast ratio.

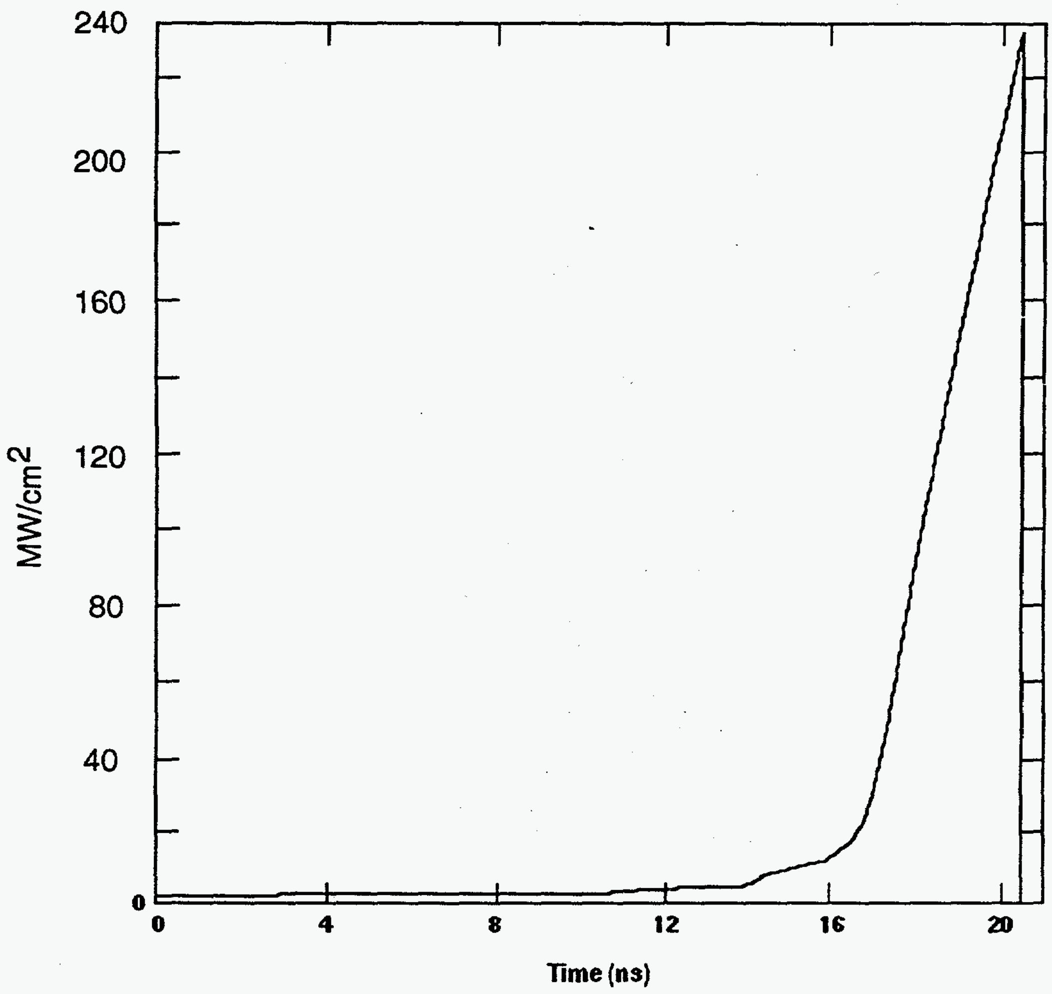

Figure 3. The temporal optical pulse shape required at the preamplifier output.

The amplitude modulator device is housed in a chassis along with electrical bias and pulse generators, and diagnostic pickoffs, as shown in figure 4. The chassis is essentially a digitally programmable arbitrary waveform generator for light, and comprises the heart of the MOR pulse generation system.

The modulator chip

The amplitude modulators form the oscillator light into "shaped" pulses, with a temporal power profile determined by low voltage electrical waveforms. These modulators are lithium niobate, integrated optical waveguide devices, similar to those commercially available for digital communications. A similar device has been tested on the Beamlet demonstration laser with excellent results (5).

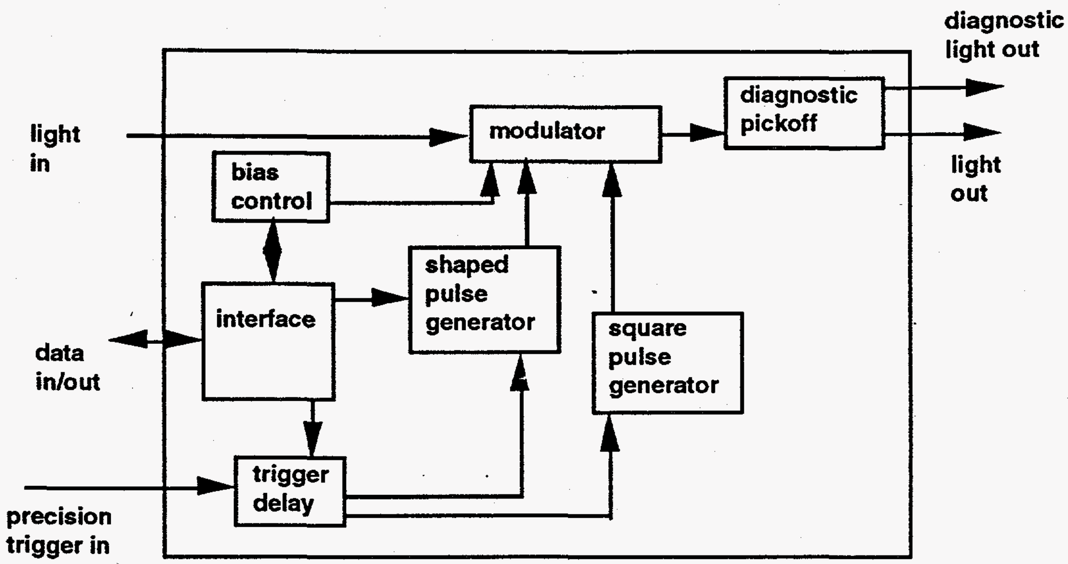

Figure 4. The amplitude modulator chassis.

The modulator chip has two amplitude modulators optically in series, to increase the on/off extinction ratio, and to provide for two separate modulation inputs. One input defines the shape of the optical pulse, and the other applies a square gate to sharpen the rise and fall times and remove any spurious post-pulse signals created by the shaper. Each of these modulators must be electrically biased to prevent transmission of the input optical pulse until the appearance of the pulse shaping waveform. The extinction of light in the "off" state is 10^5 below the "on" state.

Pulse shape generator

The input electrical pulse shape to the each modulator is provided by a dedicated arbitrary waveform generator. One concept for this is shown in figure 5. The circuit consists of high speed, low voltage GaAs FET transistors connected, as shown, to a central transmission line, and triggered by symmetric trigger transmission lines. This trigger pulse is first incident upon the leftmost GaAs circuit, with a small fraction of the trigger coupling from the trigger line to the transistor gate through the small coupling capacitor. The transistor is turned on to a degree determined by the initial bias. The inverse of the trigger pulse is imparted to the pulse forming transmission line. The left going portion of the pulse is absorbed by the terminator, while the right going pulse passes the next transistor just before it, in turn, is activated to make a similar replica of the trigger pulse. In this way, the electrical pulse shape is synthesized. The actual shape of the pulse is controlled by a series of twenty 12 bit dual digital-to-analog converters which provide the transistor bias voltage. The final pulse shape is amplified from a nominal 2 V peak to as high as 10 V by a power GaAs FET linear amplifier. The resultant pulse drives the amplitude modulators, which require less than 10 volts to transmit at full amplitude.

Timing and triggering

Both pulsers are triggered from a high resolution, low jitter digital delay generator, which determines the timing of the optical pulse in each arm. During initial setup, gross differences in arm length are compensated by cutting the 200 m long transport fibers. Finer variations are adjusted using the fiber distribution jumper in the MOR. Routine adjustments of the arm delays, to achieve better than 10 ps synchronization, are accomplished with the digital delays in the modulator chassis.

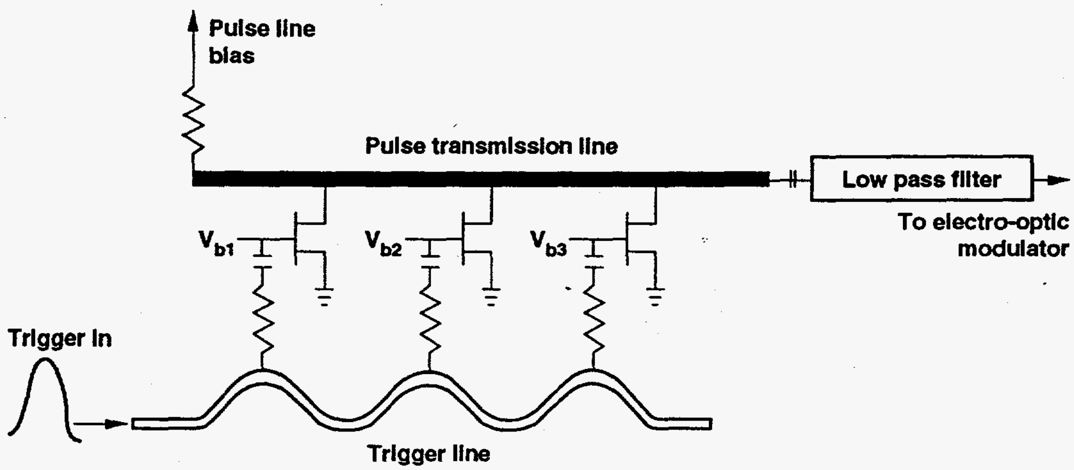

Fig. 5.3-10

Figure 5. A concept for the arbitrary electrical waveform generator.

These delays must be fed with extremely well synchronized pulses in order to preserve this simultaneity. A highly stable 100 MHz oscillator feeds the phase modulation system and the Integrated Timing System (ITS). The ITS divides this frequency and phase synchronizes the resultant 960 Hz signal with the original 100 MHz. Each cycle of the 960 Hz (chosen so that division by an integer gives 60 Hz for synchronization of video signals) initiates a master trigger signal. This signal is split and amplified in fast electronics, resulting in 192 trigger signals with low shot-to-shot jitter. Delays through the system are monitored by time interval meters to detect any long term drift.

Master Oscillator Fiber Distribution Subsystem

After the modulators, the optical pulses go via fiber to the distribution rack, which houses a patch panel similar to those used in distribution for communications networks. Fiberoptic jumpers connect the pulse shaping modulators to designated preamplifier modules, and allow for testing of the fiberoptic cables from a central location.

The fibers from the MOR to the preamplifiers represent the longest interaction length for nonlinear or dispersive effects. Fortunately, the optical power and amplitude modulation bandwidth are too low for self-phase modulation to be a problem. Stimulated Raman scattering is more likely, and the threshold for this effect is the power limit for the long fiber. Stimulated Brillouin scattering (SBS) introduces a limit on peak power which is accounted for in the fiber lengths used in the design. Experimentally, this limit has been found to be about 100 watts for a 30 ns pulse in a 20 meter long polarization maintaining fiber. The main effect which the long fibers have on the optical pulse is group velocity dispersion (GVD), which turns frequency modulation into amplitude modulation. We have modeled this effect for different bandwidths and modulation frequencies. For the lowest practical modulation frequencies, when the sideband spacing is barely resolved by the 3ω optics' transverse SBS process, required bandwidths result in acceptably small amounts of amplitude modulation.

Preamplifier Subsystem

The preamplifier brings the low energy level master oscillator signals up to the energy level required for injection into the main laser amplifier. It also spatially shapes the beam to generate a beam having a high fill factor and smooth beam profile, and to pre-compensate for non uniform gain distribution in the main beamlet amplifiers. The preamplifier must deliver a total gain exceeding 10^{10}, with minimal temporal pulse shape distortion, over a bandwidth region spanning the four different frequencies used in the laser system. The preamplifier is designed to deliver 12.5 J in an equivalent 10 ns pulse to the main laser amplifier. The basic architecture of the preamplifier package is equivalent to the preamplifier used in the Beamlet demonstration laser, and consists of three parts: a high gain regenerative amplifier, a beam expansion and shaping system, and a final four-pass amplifier stage (figure 6). Each beamlet has its own independent preamplifier. All preamplifiers in the system are identical and interchangeable to allow for easy service and maintenance.

Regenerative amplifier

A conventional ring regenerative amplifier (RA) using two diode-pumped Nd:glass laser heads provides the bulk of the gain in the preamplifier. The shaped pulse from the MOR is delivered through a single-mode, polarization-preserving fiber, is trapped by a Pockels cell in a polarization-selective ring cavity until the required output energy of 8 mJ is achieved, and the Pockels cell dumps the pulse out of the cavity. A Faraday rotator protects the sensitive waveguide circuits from returning ASE emission. In order to maintain optimum signal-to-noise ratio, the cavity is designed as a self-imaging, spatially-filtered relay system using two lenses with focal length equal to one-fourth of the round trip length. The 9 m round trip length is determined by the required gain window of 20 ns, and the rise and fall time of the 10 mm aperture KD*P Pockels cell. The transverse single-mode profile of the injection fiber is relayed into the mode-defining aperture of the ring cavity. Transformation into a cavity eigenmode occurs in three round trips and is quite efficient (~ 70 %).

Two Nd:glass amplifier heads provide a net gain of eight per roundtrip. The amplifier is a 4 mm diameter, 50 mm long APG-1 rod, end-pumped by a diode laser array coupled through a light guide. The pumped end surface has a highly reflective coating for the laser pulse, such that it can be used in double pass mode. The diode arrays provide 4.8 kW in a 300 μs pump pulse to achieve a double pass gain of 1.1 Np. The increased pumping efficiency makes it possible to drive the RA at a repetition rate of 1 Hz (equivalent to 30 % of the thermal fracture limit) . This rate is sufficiently high for set-up, test and alignment. The long beam path of the RA is folded using the double pass amplifiers as near normal reflectors to reduce surface area requirements and increase mechanical stability.

Spatial beam shaping section

The nearly Gaussian output beam profile of the regenerative amplifier is converted to the beam profile required for injection in the main amplifier. A schematic diagram of the beam shaping section is shown in figure 7.

The RA pulses are first expanded through a 21 x magnifying telescope. The central 25 x 25 mm^2 area is converted into a tophat beam by a fixed anti-Gaussian transmission filter. A flat-topped (22.5 x 23.7 mm^2) beam with inverted Gaussian apodized edges is created by a serrated aperture, in combination with spatial filtering to remove high frequency modulations. Very precise serrated patterns made by electron-beam deposition of chromium have been demonstrated successfully on the Beamlet Demonstration System. This serrated aperture forms the primary beam edge profile that will be relayed through the whole laser system.

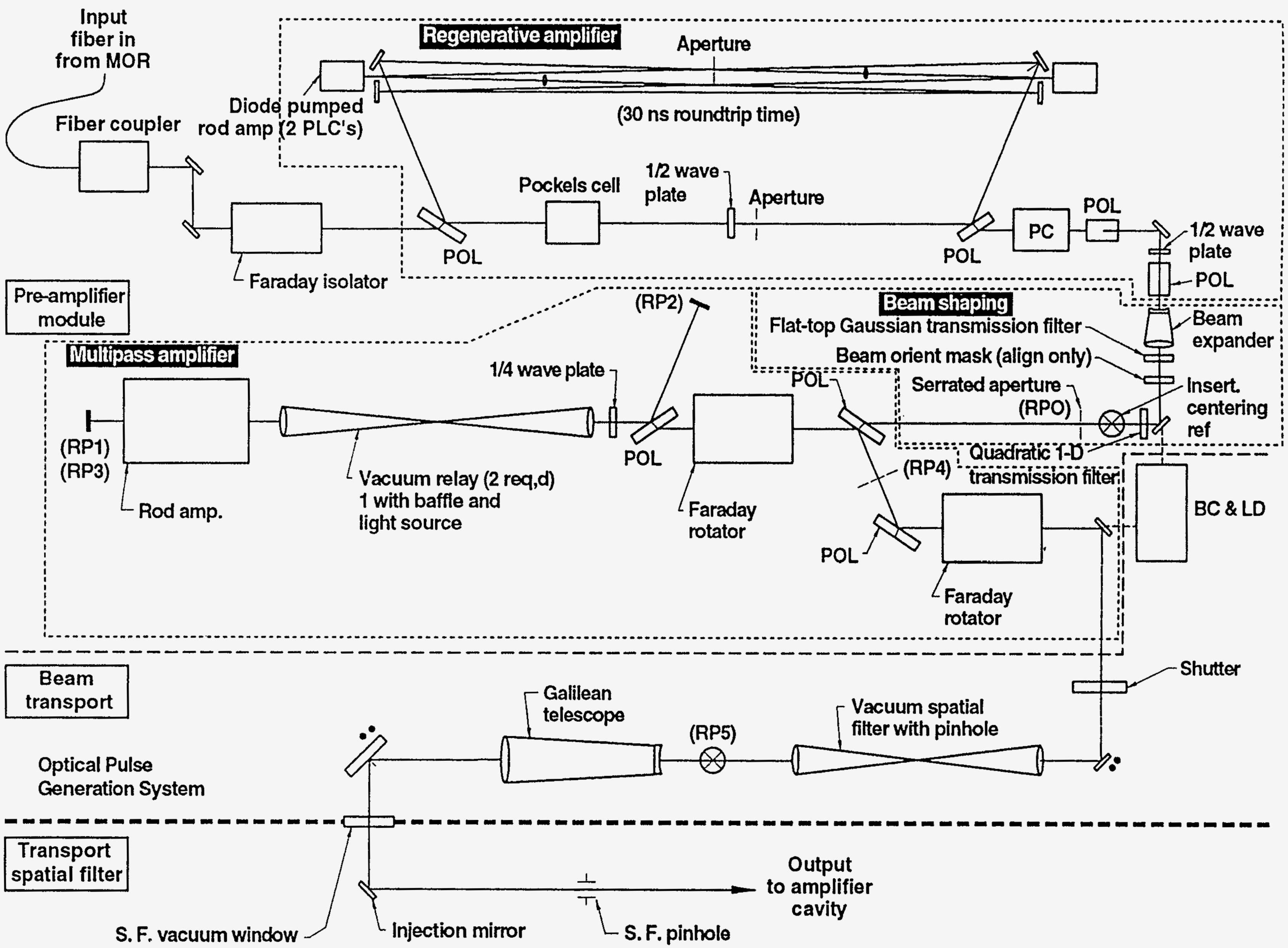

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Fig 5.3.1-17 (192 + 240)

Figure 6. The preamplifier subsystem.

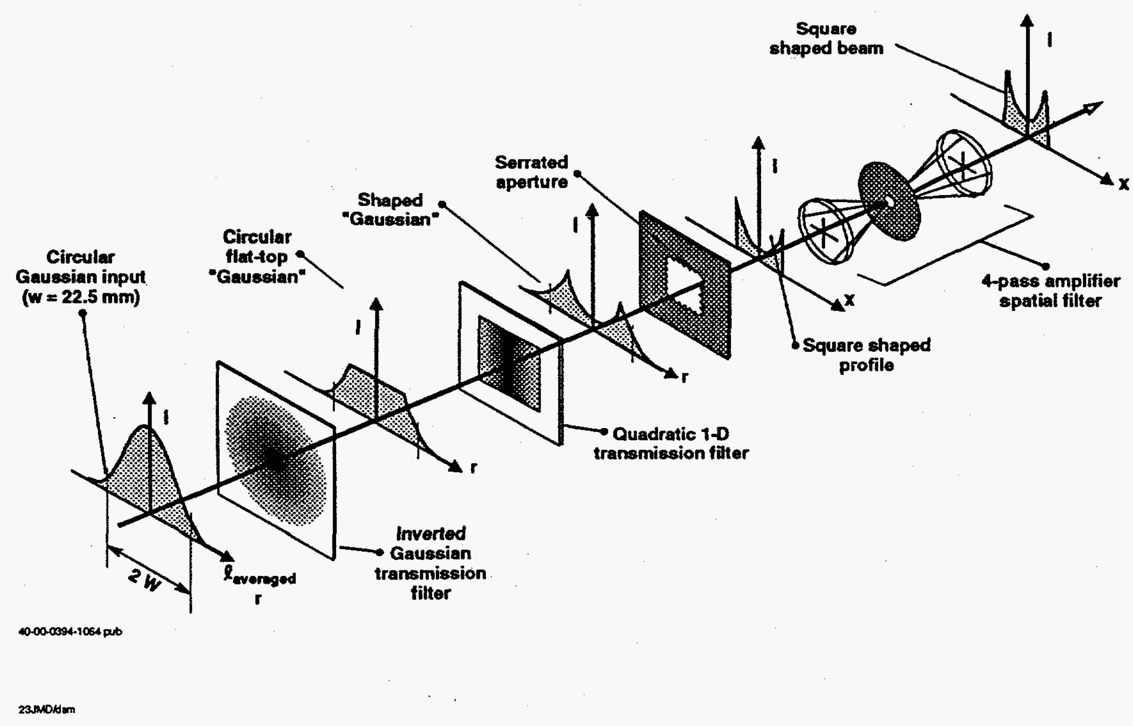

Figure 7. The spatial beam shaping optics.

Additional shaping is required to precompensate ASE induced gain roll-off in the main amplifiers. The generic shape is a 1-D parabolic profile with 5:1 edge-to-center intensity contrast. This contrast will be achieved using shaped metallic transmission filters, similar to the Gaussian beam filter. The fluence in this section (< 1.6 mJ/cm^2) is well below the damage threshold of this type of filters.

Four-pass preamplifier section

The final preamplifier section uses a rod amplifier to boost the mJ output energy of the beam shapers to 12.5 J (energy delivered in a 0.85 fill factor pulse). The total gain is achieved by four passes through the amplifier using a Faraday rotator and quarter-wave-plate combination (figure 6).

Large aperture permanent magnet Faraday rotators will be used in the preamplifier. A 100 mm aperture Faraday rotator, manufactured by Passat Enterprises (Russia), was recently installed and successfully tested in the Beamlet Demonstration System front-end four-pass preamplifier. These permanent magnet devices are cost effective and perform better than pulsed magnet Faraday rotators.

The serrated aperture located in the spatial beam shaping section is image relayed through the four-pass amplifier by two, unity-magnification vacuum telescopes, one of which is configured as a spatial filter. This configuration allows the separation of the four-passes at the focal plane of the spatial filters by imposing a small pointing offset of the beam through the first relay plane. Because of this offset the amplifier requires a rectangular clear aperture of 2.5 x 5.1 cm^2. The foci of the four-passes are arranged on a single line. A suitable mask in the pinhole plane prevents cross-coupling and parasitic oscillations in the cavity.

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