A COMPACT, TOTALLY PASSIVE, MULTI-PASS SLAB LASER AMPLIFIER BASED ON STABLE, DEGENERATE OPTICAL RESONATORS

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Abstract

Low energy, picosecond pulse oscillators typically require several orders of magnitude amplification to be useful in kHz satellite laser ranging systems, altimetry, or other applications. The present paper describes a totally passive amplifier design, based on degenerate optical resonators, which permits high multipass amplification of ultrashort pulses in a compact package, requires no active switching components, and should be relatively simple to align.

INTRODUCTION

New kilohertz satellite laser ranging systems rely on either passively Q-switched microchip or SESAM (**SE**miconductor **S**aturable **A**bsorbing **M**irrors) laser oscillators for the generation of picosecond pulsewidths. Microchip lasers (e.g. SLR2000) typically generate several microjoule pulse energies at few kHz rates with pulsewidths on the order of a few hundred picoseconds. SESAM devices (e.g. Graz) can produce much shorter pulses between 10 and 25 psec but with significantly lower energies, typically sub-microjoule. Furthermore, if one operates at kHz fire rates, the amplifiers can be pumped with CW diode laser arrays for longer life and reliability, but the resulting gain per pass is relatively low compared to pulse-pumped systems. As a result, the pulse must pass through several stages of low-gain amplification in order to reach pulse energies of several hundred microjoules required for robust photon-counting of satellite returns. In the NASA SLR2000 system, the oscillator pulse is passed six times through a single amplifier head using three carefully aligned mirrors while, in the High-Q system used at Graz, the SESAM oscillator pulse is input to a relatively large regenerative amplifier with complex pulse switching electronics followed by a conventional amplifier. As an alternative, we propose a totally passive, multipass amplifier based on the concept of "stable degenerate optical resonators" [Ramsay and Degnan, 1970]. A comparison of the three multipass amplifier techniques is illustrated in Fig. 1.

STABLE DEGENERATE OPTICAL RESONATORS

The characteristics of any optical resonator are defined by the radii of curvature of two mirrors, b_1 and b_2, and the distance d between them. Paraxial rays will never walk out of the resonator, i.e. the resonator is "stable", if the following stability condition is satisfied

$$0 \le \left(1-\frac{d}{b_1}\right)\left(1-\frac{d}{b_2}\right) \le 1 \qquad (1)$$

At certain mirror separations, the resonator becomes "degenerate" and can be characterized by an integer N. These discrete separations are defined by the equation

$$d_{\pm}(N,K) = \frac{b_1+b_2}{2} \pm \frac{1}{2}\sqrt{b_1^2+b_2^2+2b_1b_2\cos\left(\frac{2pK}{N}\right)} \qquad (2)$$

$K=0$ for $N=1$
$1< K<N/2$ for $N > 1$
provided $K >1$ is not divisible into N

For each value of K and N, there are two distinct separations which produce the degeneracy. Table 1 illustrates the valid values for K up to N =8

N =	1	2	3	4	5	6	7	8
K=	0	1	1	1	1	1	1	1
					2		2	3
							3	

Table 1: Valid K-values as a function of the degeneracy factor, N.

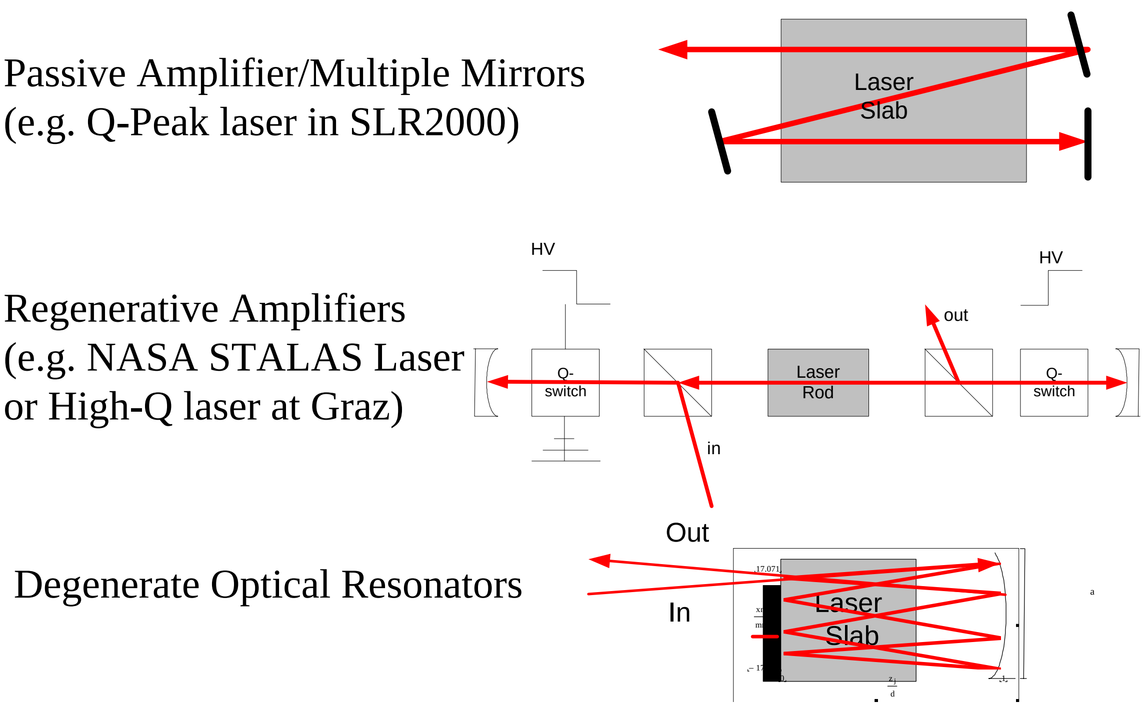


Figure 1: Some multipass amplifier approaches.

Degenerate resonators exhibit a number of interesting physical effects, among them:

- The Hermite-Gaussian (TEM_{mnq}) resonator modes divide into N discrete frequencies separated by c/2NL where L is the resonator length; thus, N=1 represents the highest degeneracy where all spatial modes oscillate at the same frequency.
- Hole-coupled lasers exhibit large power losses because the frequency-degenerate TEM modes can couple together to create a low loss composite mode with a null at the coupling hole
- Internal ray paths can be defined which repeat themselves after N round trips in the resonator

It is this last feature which suggests their use in passive multipass amplifiers.

SPECIAL CASE #1: SYMMETRIC RESONATORS

If the two mirror radii of curvature are equal ($b_1 = b_2 = b$) , the degeneracy equation simplifies to:

$$d_{\pm}(N,K) = b\left[1 \pm \cos\left(\frac{pK}{N}\right)\right]$$

Figure 2 displays the resonance positions of a symmetric resonator for N = 1 to 6. The vertical scale indicates the level of degeneracy, N.

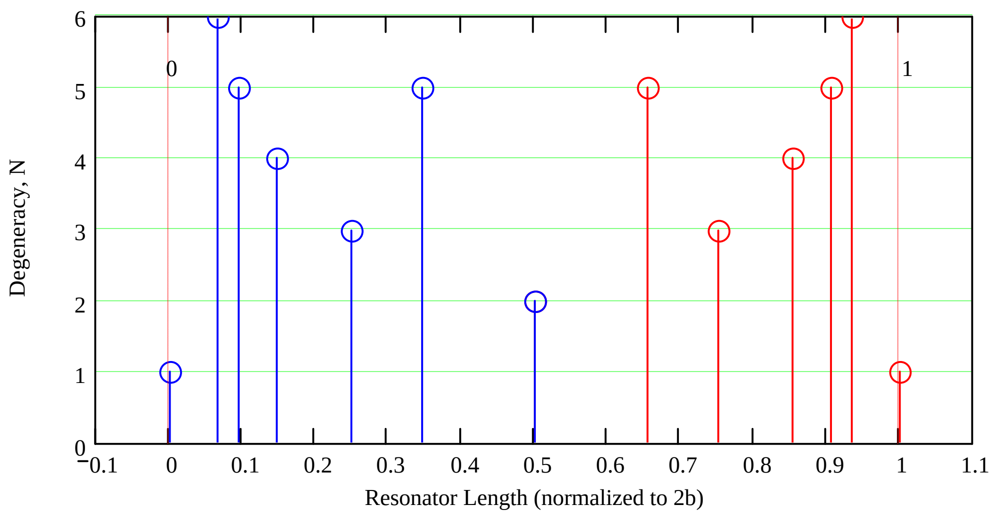
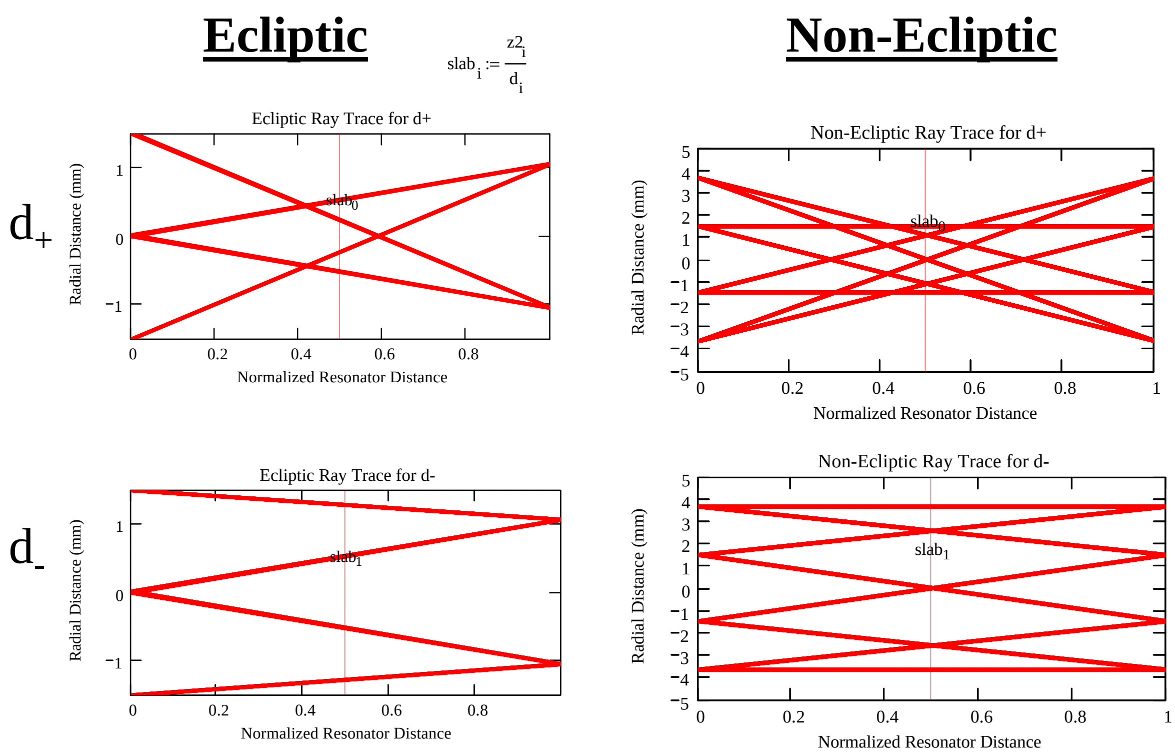


Figure 2: Degenerate mirror separations for a symmetric resonator for N = 1 to 6. The stable range is 0 $\leq$ d $\leq$ 2b. The d_+ and d_- positions are indicated by the red and blue lines respectively.

For each degenerate separation, there are two types of ray paths, "ecliptic" or "non-ecliptic", as illustrated in Figure 3 for N = 4 and K =1. Ecliptic rays make N passes through the amplifier slab before retracing the same path in the opposite direction. Non-ecliptic rays, on the other hand, never retrace the same path and therefore have the following potential advantages over ecliptic rays:

1. The angularly separated input and output beams do not require additional optical isolation between the oscillator and amplifier
2. There is no need for an independent means (e.g. polarization rotation) of separating the input and output beams
3. The circulating beam samples more of the pumped amplifier volume for better energy extraction

Ecliptic ray paths, on the other hand, may offer advantages in terms of ease of alignment since the input and output beams are coaxial and normal to the reflecting surface of the input mirror. Furthermore, as we shall see later, ecliptic paths also lend themselves more easily to variable pass amplifier systems.



(a) **(b)**

Figure 3: Ray traces for a symmetric resonator with degeneracy N =4 and K =1; (a) Ecliptic ray traces for d_+ (top) and d_- (bottom) ; (b) Non-ecliptic ray traces for same geometries.

SPECIAL CASE #2: FLAT-CONCAVE RESONATORS (b_2 = ¥)

If one mirror radius of curvature is infinite ($b_2 = \infty$) , the degeneracy equation simplifies to:

$$d\ (N,K) = \frac{b_1}{2}\left[1 - \cos\left(\frac{2pK}{N}\right)\right]$$

Figure 4 displays the resonance positions of the flat-concave resonator for N = 1 to 6. The vertical scale again indicates the level of degeneracy, N. Unlike the general or symmetric resonator cases, there is now only one degenerate mirror separation for each value of N and K. For each degenerate position, one can again define ecliptic and non-ecliptic ray paths which repeat themselves after N round trips through the resonator.

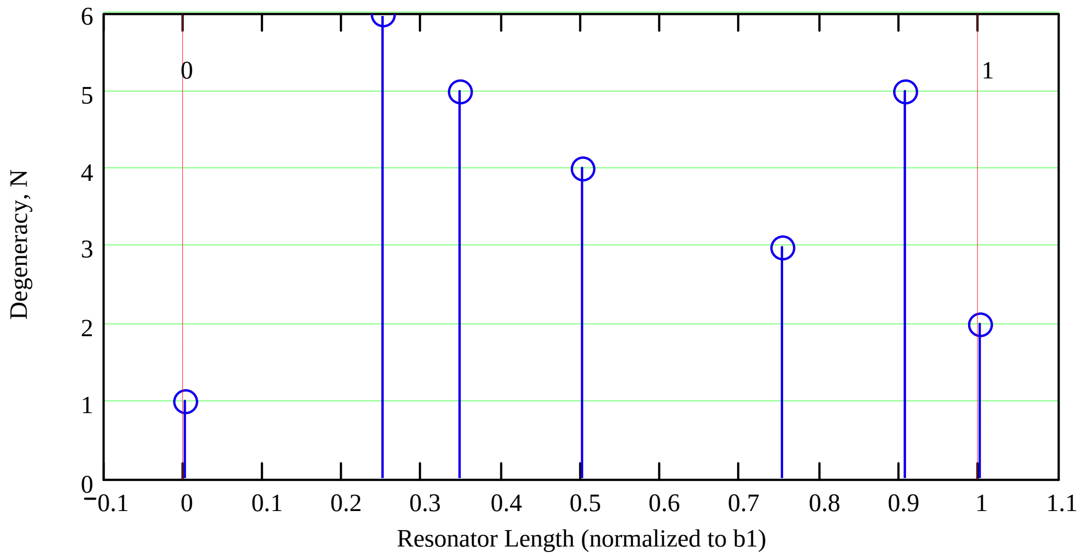
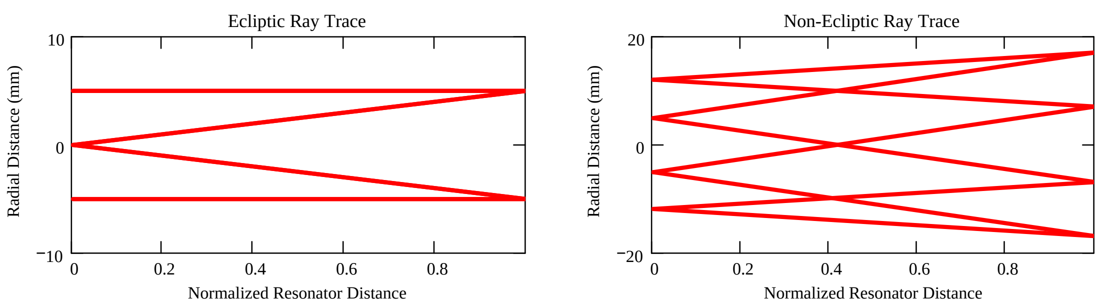


Figure 4: Degenerate mirror separations (normalized to the radius of curvature b_1 of the non-flat mirror) for the generalized flat-concave resonator for N = 1 to 6. The stable region is now defined by $0 \leq d \leq b_1$.



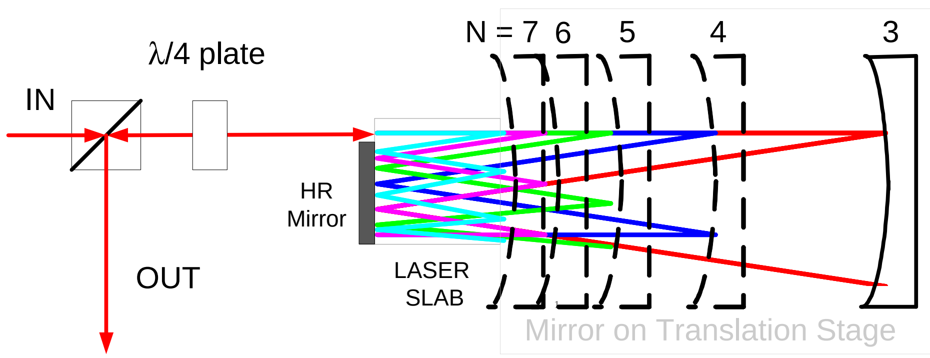
(a) **(b)**

Figure 5: Ray traces for a Flat-Concave resonator with degeneracy N =4 and K =1; (a) Ecliptic ray trace; (b) Non-ecliptic ray trace. The flat mirror is assumed to be located to the left of each ray trace.

VARIABLE PASS AMPLIFIER DESIGN

Figure 5(a) suggests a design for a simple variable pass amplifier. As illustrated in Figure 6, the incoming collimated p-polarized beam from the oscillator passes through the polarizer and is rotated to circular polarization by a quarter-wave plate. Assume that the left edge of the slab is coated with a highly reflecting mirror at 1064 nm except for a small section at the top which is antireflection (AR) coated. The input beam is then inserted normal to the slab surface in the AR-coated region, makes an arbitrary number of passes (2N) through the amplifier dependent on the positioning of the single translatable mirror on the right, exits the multipass amplifier through the same AR-coated surface as the entry beam, is rotated to s-polarization by the second pass through the quarter-wave plate, and is reflected off the input polarizer. Diode pumping of the slab can be accomplished through the edges of the slab or through the top of the slab The amplifier design also transfers the Gaussian properties (radius, phasefront curvature) of the input beam to the exit beam at all degenerate mirror separations since the round trip ray matrix for the resonator taken to the Nth power always equals the identity matrix [Ramsay and Degnan,1970]. Thus, the exit beam will have the same spot size and divergence as the input beam [Degnan, 2004].

In order to suppress self-oscillations along or near the amplifier optic axis where the two mirror surfaces are approximately parallel, it may be necessary to introduce a region of low reflectivity in the center of the spherical mirror by either (1) leaving the center uncoated, (2) AR-coating the center, or (3) introducing a central hole. This has no effect on the amplification since the ecliptic rays entering from the flat side of the resonator never reflect off the center of the spherical mirror. However, the diameter of the low reflectivity area will impose an upper limit on the number of roundtrip passes that can be achieved without having the amplified beam attenuated by the low reflectivity spot.



K = 1

Figure 6: Concept for a compact, passive, multipass amplifier based on ecliptic rays in a flat-concave degenerate resonator. The degeneracy N, and the number of passes through the amplifier (2N), can be varied by moving the spherical mirror on a precision translation stage. Differently colored rays are associated with different values of N (red =3, blue = 4, green = 5, etc)

SUMMARY

Microchip and SESAM oscillators can generate picosecond pulses at multi-KHz rates but only at low single pulse energies (several microjoules or less). Since many applications (SLR, 3D imaging lidar, etc.) require pulse energies ranging from several tens of microjoules to several millijoules, there is a general need for high amplifications in a compact, efficient, diode-pumped package. Furthermore, since CW-diode pumped amps typically have low single pass gains, many passes through the amplifier may be required to reach the required pulse energies and to extract the stored energy efficiently. Regenerative amplifiers can achieve this, but they are usually quite large and require high speed, high voltage electro-optic switches Totally passive degenerate resonator multipass amplifiers are an attractive alternative to multiple mirror systems as used in SLR2000 and can potentially provide :

- High multipass gain in a compact, easily aligned package

- A fair amount of isolation from the oscillator and reduced internal feedback for suppressing self-oscillations within the amplifier
- Variable number of passes with one translating mirror which can be set for optimum performance or compensate for a degradation in oscillator power
- Excellent beam control since it preserves the gaussian parameters of the input beam at the output due to periodic refocusing

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REFERENCES

Ramsay, I. A. and J. J. Degnan, "A Ray Analysis of Optical Resonators Formed by Two Spherical Mirrors", *Applied Optics*, Vol. 9, pp. 385-398, February, 1970.

Degnan, J.J., “Ray Matrix Approach for the Real Time Control of SLR2000 Optical Elements”, these proceedings, 2004.