JAERI-Research
2003-017

DEVELOPMENT OF A HIGH-ENERGY, ULTRABROADBAND TI:SAPPHIRE RING REGENERATIVE AMPLIFIER

September 2003

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日 本 原 子 力 研 究 所
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編集兼発行　　日本原子力研究所

JAERI-Research 2003-017

Development of a High-energy, Ultrabroadband Ti:sapphire Ring Regenerative Amplifier

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(Received July 14, 2003)

We have developed a high-energy, ultrabroadband Ti:sapphire ring regenerative amplifier capable of producing in excess of 20 mJ output at a 10 Hz repetition rate. The technique of chirped-pulse amplification is used to generate two-color, time-synchronized pulses, with central wavelength separations up to ~ 120 nm and with a total energy of 10 mJ by using a regenerative pulse shaping technique.

Keywords: Laser Amplifiers, Ultrafast Optics, Dispersion Control, Optical Pulse Shaping, Gain Control, Optical Pulse Compression, Solid-state Lasers

JAERI-Research 2003-017

高出力・広帯域リング型チタンサファイア再生増幅器の開発

日本原子力研究所関西研究所光量子科学研究センター
山川　考一

（2003年7月14日受理）

我々は、繰り返し数10 Hz、出力エネルギー20 mJ以上を発生する広帯域リング型チタンサファイア再生増幅器を開発した。チャープパルス増幅法と再生パルス整形技術により、出力エネルギー10 mJ以上の2波長フェムト秒レーザー光（波長間隔120 nm）の発生に成功した。

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1. INTRODUCTION

Intense radiation from femtosecond lasers has opened up new areas of research in physics, chemistry and medicine. The application of the chirped-pulse amplification (CPA) technique [1] to broadband solid-state lasers makes possible the production of multiterawatt femtosecond pulses [2, 3] Recently this technique was extended to produce 100 TW pulses of ~ 20 fs in duration [4]. Most of these systems employ the technique of regenerative pulse shaping to overcome gain narrowing during amplification [5]. To date, terawatt-class and multiterawatt, sub-20 fs Ti:sapphire laser systems have been developed by using this technique [6, 7]

There has been considerable activity in the development of high power, tunable infrared pulse lasers for biomedical and material research applications as well as quantum control of chemical reactions. For example, a free-electron laser operating at 6.45 μm, 1 μJ per pulse energy has achieved remarkable tissue ablations results without serious collateral damage [8]. Two-color, high-power ultrashort pulse lasers will allow the generation of ultrashort pulses in the infrared by frequency mixing in nonlinear crystals. Two-color operation has been achieved previously by synchronous pumping of a dye laser [9] and by use of two separated cavities [10] or by use of single cavity in a Ti:sapphire laser [11]. A wavelength separation of up to 90 nm has been demonstrated in a mode-locked Ti:sapphire laser [10]. However, the energy per pulse of these systems is of the order of nJs. More recently, pulse energy of 7.4 μJ has been achieved at wavelengths of ~ 10 μm by difference frequency mixing of two-color pulses from a dual-wavelength Ti:sapphire CPA system [12]. Outputs with a total energy of 1.5 mJ and 15 mJ were generated with a Ti:sapphire regenerative [13] and with a multi-pass amplifiers [12], respectively. Both systems required careful gain control of the two-color pulses during amplification. The cavity mirror bandwidth limited the tuning range to between 800 and 890 nm. In our previous experiments, two-color pulses centered at 760nm and 850 nm were created from a single broadband pulse and were simultaneously amplified in a linear cavity Ti:sapphire regenerative amplifier by incorporating the technique of regenerative pulse shaping [14] However, the generation of tunable pulses at 6.45 μm by frequency mixing in nonlinear crystals, for example, requires two-color pulses at 750 and 850 nm, respectively. To date no two-color amplification system has reached this important milestone.

Further extension of the bandwidth of the amplified pulses is presently limited by the bandwidth of high-damage-threshold broadband dielectric elements. A fundamental challenge for all short pulse CPA amplifiers is the development of broadband intracavity elements in the regenerative amplifier which will minimize spectral gain narrowing. The regenerative amplifiers consist of cavity mirrors, polarizers a gain medium and a Pockels cell. The thin film dielectric polarizers have achieved efficient transmission ($T_p > 98\%$) from 700 to 950 nm. However high power normal incidence dielectric mirrors have 99% reflectivity over a more limited range, from 750 to 850 nm. Therefore the mirror set of the regenerative amplifier is the primary spectral-limiting element. Since s-polarized dielectric mirrors always have a larger bandwidth than those of normal incidence or p-polarization, a ring-type regenerative amplifier utilizing 45 degree, s-polarized dielectric mirrors will have larger bandwidth than conventional linear regenerative amplifier geometries. It should be noted that we have previously very briefly reported on the preliminary result of a broadband amplification in a Ti:sapphire ring regenerative amplifier [15].

In this paper we report on the new development of an ultrabroadband Ti:sapphire ring regenerative amplifier for applications of two-color and/or ultrashort pulses amplification. We have generated two-color, time-synchronized pulses, with central wavelength separations up to 120 nm and with a total energy of 10 mJ. This is the highest-energy, two-color chirped-pulse regenerative amplifier with a largest bandwidth to our knowledge.

2. RING REGENERATIVE AMPLIFIER

A layout of a vertical, s-polarized, ring regenerative amplifier is shown in Fig.1. The regenerative amplifier is a stable TEM_{00} cavity with a mode size in the Ti:sapphire rod as large as 2.0 mm in diameter. The TEM_{00} cavity is made by a 1.5 m focal-length lens placed to close to the Ti:sapphire crystal. The resonator is 3 m long and uses four flat cavity mirrors. The cavity mirrors support 99% reflectivity HFO_2 dielectric coating for s-polarization from 725 to 900 nm (CVI Laser). It should be noted that the

HfO_2 dielectric coating gives a larger bandwidth than that of conventional TaO_2 dielectric coating. The MgF_2 anti-reflection coated Ti:sapphire crystal is 7 mm long with 0.15 wt% doping (Crystal Systems). The crystal is end pumped by the frequency-doubled Q-switched Nd:YAG laser to produce 7 ns pulses at a 10 Hz repetition rate. A 50 cm focal-length lens images the pump beam onto the Ti:sapphire crystal with the pump fluence on the first face of the crystal estimated to be ~1.2 J/cm^2 Pulse injection into the regenerative amplifier is achieved by an intracavity Pockels cell (Cleaveland Crystals) placed between thin film dielectric polarizers (Alpine Research Optics). The Pockels cell is coated with a sol-gel material. The thin film polarizers (TFP) are coated 85% s-polarization reflectivity and >98% p-polarization transmission from 700 to 950 nm. A high voltage pulse generator (Medox Electro-Optics) capable of producing up to 6 kV pulses with a FWHM of 5 ns is used to drive the Pockels cell to a half wave voltage for pulse injection and rejection.

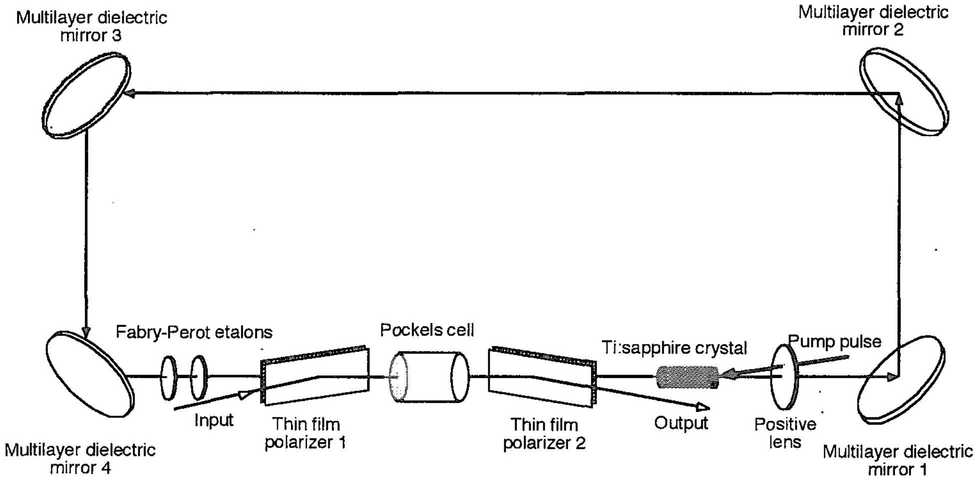

Fig.1: Optical layout of a vertical, s-polarized Ti:sapphire ring regenerative amplifier.

In our experiment the low energy seed pulse is obtained from an all-solid-state mirror-dispersion-controlled Ti:sapphire laser which produces ~10 fs, 2 nJ pulses at a 83 MHz repetition rate. The bandwidth of the seed pulses is ~ 120 nm at a central wavelength of 790 nm. The temporal pulse stretching is necessary to avoid nonlinear effects associated with the intensity-dependent refractive index in the amplifier. The seed pulses were stretched by a factor of 100,000 in an all-reflective, cylindrical-mirror-based pulse stretcher [16]. This design allows the compensation of dispersive phase errors up to fifth-order and eliminates spatial inhomogeneities. Positive group delay dispersion produces a positively linear chirp to widen the pulses from 10 fs to 900 ps. After the Faraday isolator, the s-polarized pulses are injected into the ring regenerative amplifier through the TFP 1. Pulsing the Pockels cell to its half-wave voltage traps a single pulse inside the cavity, where it remains until the pulse buildup reaches a threshold value. The p-polarized pulse passes through the TFP 2 and then passes through the Ti:sapphire rod. After passing through the rod the now p-polarized pulse is incident upon mirror 1 at 45 degrees and is reflected to the vertical direction. Although it remains the p-polarized light in the cavity, the electric field of the light on the mirrors is perpendicular to the plane of incidence (s-polarized). The pulse is then ejected from the cavity through the TFP 2 after the desired number of round trips by applying the electrical pulse again. The contrast ratio, defined as the ratio of the intensities of a main pulse to a leakage through the TFP is typically 10^3:1.

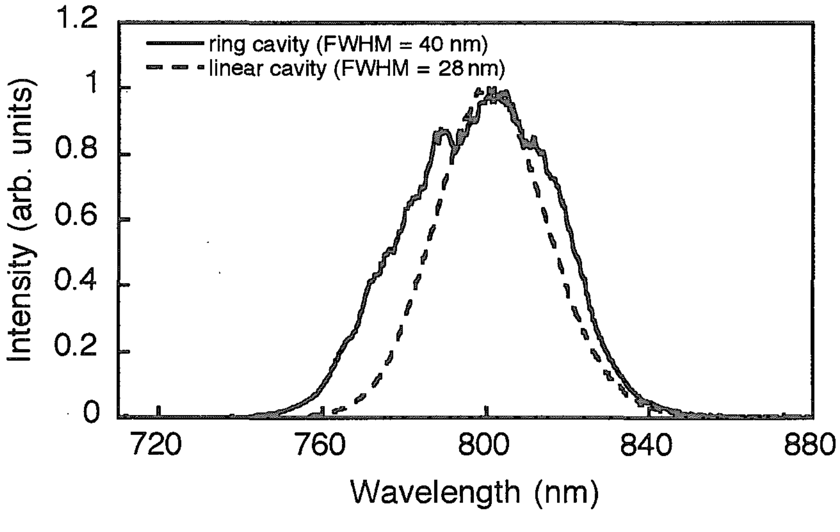

Fig.2: Measured ASE spectra for a Ti:sapphire ring- (solid line) and linear-cavity (broken line) regenerative amplifiers, respectively.

The buildup time depends on the pump energy and its typically 190 ns, which corresponds to the number of round trips of 19 for pump energy of 50 mJ. As much as 20 mJ of output energy was obtained for pump energy of 60 mJ, which gave a slope efficiency of 30%. The output is primarily limited by the available output energy of the pump laser and not optical damage of the intracavity elements. As shown in Fig. 2, the unseeded ASE spectra for both ring- and linear-cavity regenerative amplifiers measure 40 nm and 28 nm, respectively, centered at 800 nm. This clearly demonstrates the effectiveness of the ring-cavity regenerative amplifier both in terms of energy and bandwidth of the amplified pulse compared with the linear-cavity regenerative amplifier [14]. The beam quality of the amplified pulse is a TEM_{00} Gaussian mode.

3. TWO-COLOR AND ULTRABROADBAND AMPLIFICATION

We have tested two-color chirped-pulse amplification starting from the single pulse output of the self-mode-locked Ti:sapphire laser. Recently, we have demonstrated the technique of regenerative pulse shaping to overcome gain narrowing [5, 14]. This is accomplished in regenerative amplification schemes by placing a frequency dependent attenuation inside the amplifier cavity. We have investigated angle-tuned thin etalons to generate the two-color pulses in the regenerative amplifier. With proper adjustment of the angle of the etalons, the gain profile of the regenerative amplifier is modified and gain on line center can be suppressed. The etalons that we used in this experiment are two, 3 μm thick uncoated nitrocellulose pellicles. They are mounted on rotation stages for angle tuning. With two etalons, it was possible to independently control the blue and red sides of the amplified spectrum without unwanted amplification at the peak of the gain profile. We have amplified pulses centered at 740 nm and 861 nm simultaneously as shown in Fig. 3. The pulse duration of the two color pulses are calculated to be 104 ps for the 740 nm pulse and 132 ps for the 861 nm pulse, respectively. Each individual pulse had up to ~ 5 mJ of energy before compression and < 1.5 GW/cm^2 of intensity inside the regenerative amplifier which corresponds to the intensity well below the damage threshold of the optical components. After amplification, the two pulses are then compressed by double passing through three compression gratings and two back reflection mirrors. Typical, independent pulse durations are measured to be ~ 150 fs by using a single-shot autocorrelator. Two color beams were spatially and temporally separated by tilting and moving one of the back reflection mirrors.

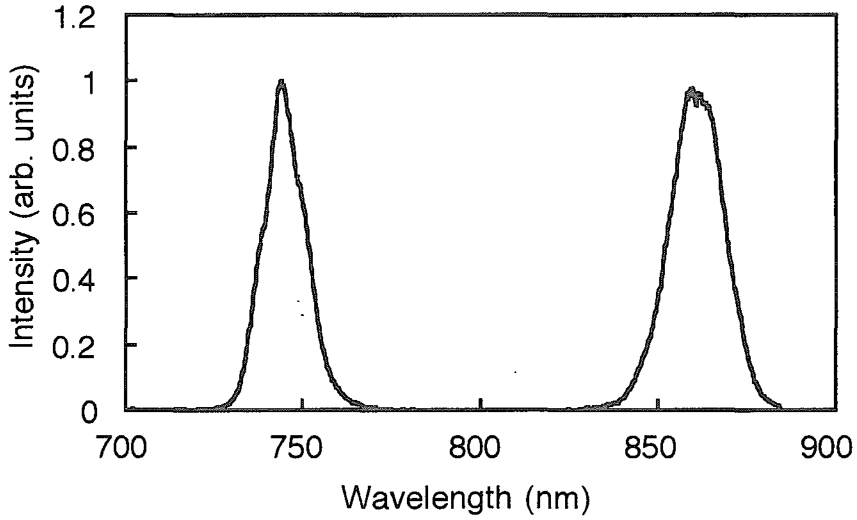

Fig.3: Two-color spectra from the Ti:sapphire regenerative amplifier.

In addition, amplification of an ultrabroadband femtosecond seed pulse was also investigated. By selectively amplifying the wings of the spectrum with the etalons in the cavity, the spectrum of the amplified, stretched pulse was broadened to 128 nm at FWHM as shown in Fig. 4. The edges of the shortest and longest wavelengths of the amplified spectrum are 742 and 875 nm, respectively. Thus, the amplified spectrum at FWHM, is in fact, broader than the input spectrum at FWHM. The Fourier transform of the amplified spectrum corresponds to an ~ 12 fs pulse. In order to obtain a shortest pulse by compressing this broadband, chirped pulse, it is necessary to compensate higher-order phase distortions over entire bandwidth. This could be achieved by incorporating novel devices such as an AOPDF [17], a liquid-crystal spatial light modulator [18] and a deformable mirror [19].

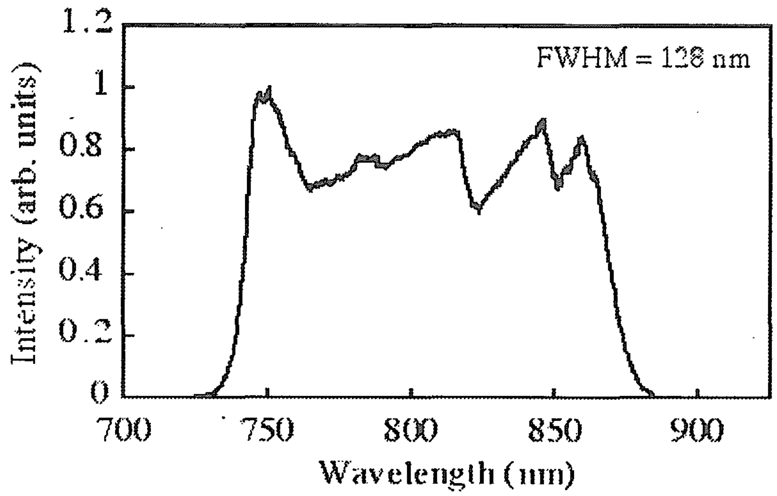

Fig.4: Measured amplified spectrum of the single broadband pulse from the Ti:sapphire regenerative amplifier.

4. CONCLUSION

In conclusion, we have developed a vertical, s-polarized, ring regenerative amplifier for two-color and/or ultrashort pulse amplification. The output energy of the regenerative amplifier is in excess of 20 mJ, which is limited by the available output energy of the pump laser. This amplifier has produced the widest separation for two-color amplification of any system to date and has demonstrated gain “broadening” of a single input pulse beyond its input FWHM bandwidth. We have generated two-color, time-synchronized pulses centered at 740 nm and 861 nm simultaneously and with total energy of 10 mJ by using the regenerative pulse shaping technique. The high power, two-color outputs were used for the generation of tunable pulses from 6 μm to 11 μm by difference frequency mixing for the medical applications as well as coherent control of molecules.

ACKNOWLEDGEMENT

The early stages of this work were performed with C. P. J. Barty, T. Guo, C. Le Blanc, J. Squire, G. Korn, C. Rose-Petruck, F. Raksi, V. Yakovlev, and K. Wilson at the University of California, San Diego. The author would like to thank T. Kimura for his encouragement and K. Yokoyama for his useful information.

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国際単位系（SI)と換算表

表1　SI基本単位および補助単位

量	名　称	記　号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd
平面角	ラジアン	rad
立体角	ステラジアン	sr

表3　固有の名称をもつSI組立単位

量	名　称	記号	他のSI単位による表現
周波数	ヘルツ	Hz	s^{-1}
力	ニュートン	N	$m\cdot kg/s^2$
圧力，応力	パスカル	Pa	N/m^2
エネルギー,仕事,熱量	ジュール	J	N·m
工率，放射束	ワット	W	J/s
電気量，電荷	クーロン	C	A·s
電位，電圧，起電力	ボルト	V	W/A
静電容量	ファラド	F	C/V
電気抵抗	オーム	Ω	V/A
コンダクタンス	ジーメンス	S	A/V
磁束	ウェーバ	Wb	V·s
磁束密度	テスラ	T	Wb/m^2
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	℃	
光束	ルーメン	lm	cd·sr
照度	ルクス	lx	lm/m^2
放射能	ベクレル	Bq	s^{-1}
吸収線量	グレイ	Gy	J/kg
線量等量	シーベルト	Sv	J/kg

表2　SIと併用される単位

名　称	記　号
分，時，日	min，h，d
度，分，秒	°，′，″
リットル	l，L
トン	t
電子ボルト	eV
原子質量単位	u

$1\ eV=1.60218\times10^{-19}J$

$1\ u=1.66054\times10^{-27}kg$

表4　SIと共に暫定的に維持される単位

名　称	記　号
オングストローム	Å
バーン	b
バール	bar
ガル	Gal
キュリー	Ci
レントゲン	R
ラド	rad
レム	rem

$1\ Å=0.1nm=10^{-10}m$

$1\ b=100fm^2=10^{-28}m^2$

$1\ bar=0.1MPa=10^5Pa$

$1\ Gal=1cm/s^2=10^{-2}m/s^2$

$1\ Ci=3.7\times10^{10}Bq$

$1\ R=2.58\times10^{-4}C/kg$

$1\ rad=1cGy=10^{-2}Gy$

$1\ rem=1cSv=10^{-2}Sv$

表5　SI接頭語

倍数	接頭語	記　号
10^{18}	エクサ	E
10^{15}	ペタ	P
10^{12}	テラ	T
10^9	ギガ	G
10^6	メガ	M
10^3	キロ	k
10^2	ヘクト	h
10^1	デカ	da
10^{-1}	デシ	d
10^{-2}	センチ	c
10^{-3}	ミリ	m
10^{-6}	マイクロ	μ
10^{-9}	ナノ	n
10^{-12}	ピコ	p
10^{-15}	フェムト	f
10^{-18}	アト	a

(注)

1. 表1－5は「国際単位系」第5版，国際度量衡局 1985年刊行による。ただし，1 eVおよび1 uの値はCODATAの1986年推奨値によった。
2. 表4には海里，ノット，アール，ヘクタールも含まれているが日常の単位なのでここでは省略した。
3. barは，JISでは流体の圧力を表わす場合に限り表2のカテゴリーに分類されている。
4. EC閣僚理事会指令ではbar，barnおよび「血圧の単位」mmHgを表2のカテゴリーに入れている。

換　算　表

力	$N(=10^5dyn)$	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

粘　度　$1\ Pa\cdot s(N\cdot s/m^2)=10P$(ポアズ)$(g/(cm\cdot s))$

動粘度　$1m^2/s=10^4St$(ストークス)(cm^2/s)

圧	MPa(=10bar)	kgf/cm^2	atm	mmHg(Torr)	$lbf/in^2(psi)$
	1	10.1972	9.86923	7.50062×10^3	145.038
力	0.0980665	1	0.967841	735.559	14.2233
	0.101325	1.03323	1	760	14.6959
	1.33322×10^{-4}	1.35951×10^{-3}	1.31579×10^{-3}	1	1.93368×10^{-2}
	6.89476×10^{-3}	7.03070×10^{-2}	6.80460×10^{-2}	51.7149	1

エネルギー・仕事・熱量	$J(=10^7 erg)$	kgf·m	kW·h	cal(計量法)	Btu	ft·lbf	eV
	1	0.101972	2.77778×10^{-7}	0.238889	9.47813×10^{-4}	0.737562	6.24150×10^{18}
	9.80665	1	2.72407×10^{-6}	2.34270	9.29487×10^{-3}	7.23301	6.12082×10^{19}
	3.6×10^6	3.67098×10^5	1	8.59999×10^5	3412.13	2.65522×10^6	2.24694×10^{25}
	4.18605	0.426858	1.16279×10^{-6}	1	3.96759×10^{-3}	3.08747	2.61272×10^{19}
	1055.06	107.586	2.93072×10^{-4}	252.042	1	778.172	6.58515×10^{21}
	1.35582	0.138255	3.76616×10^{-7}	0.323890	1.28506×10^{-3}	1	8.46233×10^{18}
	1.60218×10^{-19}	1.63377×10^{-20}	4.45050×10^{-26}	3.82743×10^{-20}	1.51857×10^{-22}	1.18171×10^{-19}	1

1 cal＝4.18605J（計量法）
＝4.184J（熱化学）
＝4.1855J（15℃）
＝4.1868J（国際蒸気表）

仕事率　1 PS(仏馬力)
＝75 kgf·m/s
＝735.499W

放射能	Bq	Ci
	1	2.70270×10^{-11}
	3.7×10^{10}	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58×10^{-4}	1

線量当量	Sv	rem
	1	100
	0.01	1

(86年12月26日現在)

Development of a High-energy, Ultrabroadband Ti:sapphire Ring Regenerative Amplifier