

Nexts 1997

Optical Materials 1 (1997) 75-68



# Upconversion in Er<sup>3+</sup>:YAlO<sub>3</sub> produced by metastable state absorption

Richard Scheps

Menni Christend, Carted and Cares Secretizes: Genter, RDT&C Distance (MinD), Castr FM, Son Olego, CA 52151, USA

Relatived 14 August, MRB; antiquest.38 Cheeseber 1986

#### Abitrat

Upconvenies animize in BrYALCI<sub>2</sub> (BrYALCI) was predented by extendent = wavelengths analysis Wit traditions from the  $^{1}_{12/2}$  materialist wave. Both stanly state and then dependent Decreasive measurements are apprend, and the corresponder pathway is described. The operation properties into the apprendict of state materials many bandles with our-constant apprendict two-photon discreption. Upconvention and the first the  $^{1}P_{3/2}$  size in BrYALCI was not chanved.

## 1. Introduction

Over 160 th<sup>III</sup> of 550 the emission was excertly reported [1,2] for an Er<sup>3+</sup>:YAKO<sub>2</sub> (B::YALO) uppervention least. The optical connectors officiency was 1790 that is sering the highest demonstrated for this type of laser. These results' are particularly monorkside in light of the higher planess energy in YAL22 compared to fluoride-based bents such as YLP. Higher planon energies are observatisfic state lifetens and error to shortest the meantable state lifetions. This leaves the upconversion pump efficiency. For example, only low power, self-pollect operators size layer end too have been exponent for Br:YACI [3] and Th:YACI [4].

Emission in 320 am reads from excitation at wavelengths bowers 755 on and 740 am Br.YALO is onesaid in that appearements justice may be prodoord by three different energy transfer michanization. Which of these dominant is descended by the accident conditions and the specific pump wavelengths well. Two of the upconversion pump machanisms have been previously triatitified [1,5] as coupcautive energy insuffic approximation and sequenced two-photon abacquion approximation. Composition energy transfer dominant, while the analytic for the "1<sub>11/2</sub> ground note to the "1<sub>21/2</sub> state. Following tracinetion the too aclinest to the "1<sub>21/2</sub> state. Following tracinetion the too aclinest to the "1<sub>21/2</sub> state. Following tracinetion the too aclinest to the "1<sub>21/2</sub> state. Following tracinetion the too aclinest to the "1<sub>21/2</sub> state. Following tracinetion the too aclinest to the "1<sub>21/2</sub> state. Following tracinetion the too aclinest to the "1<sub>21/2</sub> state. Following tracinetion the too aclinest to the "1<sub>21/2</sub> state. To be the "1<sub>11/2</sub> with producest as boo in the "5<sub>2/2</sub> paper laser instit. Sequencial two-photon abacquion with the state if in addition to prompto the "1<sub>11/2</sub>  $\rightarrow$  "1<sub>2/3</sub> transition, whether too prompto to is the state readility state to the upper laser level.

A third pump process was explored [2] in produce 320 ore layer embasion. This mechanism is distinguided from the other 270 in that the pump wavelength is reasonal with transitions from the  $^{1}_{13/2}$ maturable store. This pump exclamion had been providently assigned [2] to pluster institution spectrum.

00775-3461/97/2 (730) Clegeright & 1997 Blocker Baktor B.V. All rights antirest. 20 10925-39625-3962597309004-6 vanion on the horis of termsh observations. The retrice forms in that the points transition originates in the notatable state of the Br<sup>3+</sup> (pa, a distinguishing characteristic of photon avalanche uptoarcavies. In addition, the hoir curput power dependence on the pump power is significantly greater theo quadratic, elasiter on that abserved the uptotropoint flotopnearce produced by physics undersche pumping.

This work was initially meleratives in provide on manifiguous biastification of plants mulerative punging as the operative mechanism initiated by excitation from the meanifold states in ErrYALG. Configuration is mentificated by observing, captain characteristic features in the appendential flow, exparent below indicate that plants avalancies operaversion is clearly but the carelation pump unchasion is fines excitation wavelengths. Afthengin 100 later measurements parameted in that [2] are everyone, the interpretation of the pump mechanism is dot.

In this work we picture the evolut of a detailed susty of uptoerconics, flucturences in ReYALC. The data upgent a pump mechanism that is a constication of oran, relatation unrary matchin and acorections, requestial two-phonon absorption. The upconversion mechanism involves "proyeting" at "trapbig" of energy (topogle the excited ionis lovels in Re<sup>3+</sup>. Looping has been discussed in the theorem is connection with the 22  $\mu$ m<sup>-1</sup><sub>11/2</sub>  $\rightarrow$ <sup>4</sup>L<sub>12/2</sub>. It later matching with the 22  $\mu$ m<sup>-1</sup><sub>11/2</sub>  $\rightarrow$ <sup>4</sup>L<sub>12/2</sub>. It later matching. Rowswer, this pump mechanism has not been anomiated with approximation heat anticalize prior in the preparatively.

#### 1 Excelses

The cylindrical StrYALO cryani was 10 mm 100g, 64 mm in diamater 404 systemat. 1,5 ar9s Br<sup>5+</sup> (p = 2.95 × 10<sup>20</sup> cm<sup>-1</sup>). \* Throughing their wis used as the permutanence and produced over \$00 mW III \$00 um with un carpet inschwidtle of in pa than 0.02 ma (0.31 mm<sup>-1</sup>). The BrYALO crysel was placed in a closed cycle balwah cryoses containing the applical windows operated 50° with respect to out addition. The lowest temperature that extend he achieved was 6.7 K and temperature control of 0.1 K was realistation. The accountments apported in data work was patierned with the crystal at 7 K. Puonearces this way also by sherving anialog elong, and at 90° with cooper th, the excitation axis. Rath missestime pandaced fittilly main. Respectotion of the appropriate Ducessneep is payorally low since only the lowest Stath land of the stated state is anotherized #5 7 K.

Emistics was detected with an archite photocultiplite tale. (PMT). The PMT was incasted balance nervow hand approval filters for fits 90° crisecution, and non-word in anajasonous with a 0.3 re-memorizacutors for the anajasonous with a 0.3 rememorization. In the anajasonous with a 0.3 rememory and a second second second second second ana blocking. Site before being: integral table the cutors and of the monochromotor.

A schematic diagram of the uppersuits and inobtain the fluctuations this is shown in Fig. 1. The pump light was showed case the expert with a 50ment into the polythese 4 pump with of 21 p.m. Radius.



Ng. L feldensis dagan af de sjeppin viki is dista financene dan 'n DrYAL'A fininden de Alexani hak kaspanis tel prifik 15 ge aktolen 189. Al repu appin aktor om viki 15 kaspanise den de aktolen aktilden viki is de 191. All prima 1920-pake <sup>1940</sup> aktolen ike aktor om anteret in ge Anternais anternatur <sup>194</sup> i aktor aktivation

tion conditions are identical to these used to produce later estation [1,2], and this could be verified by inverting an anoput coupler missor as identified in Fig. 1. A chopper and placed is the pump black path for the fixed dependent measurements. Chopping Brquencies between 30 and 30 Hz was said.

# 3. Bedgeneed

A brief summary of the fundamental concepts tripted to opconvertion in Ec.YALO is sufficient provide a framework for the discutates presented below. A more detailed description of upconversion processes in variant materials is evaluate in the limits (6). A pierdal energy level diagnee is shown in Fig. 2. The same "upconversion" generally after to processes that produce population in an avoired trans which energy enversion that of the should be any phonoi. Is Ec.YALO should not of light at approximately 600 cm itsels to 350 cm emission due to the  $2_{3/2} \rightarrow 1_{13/2}$  tomation. Under appropriate vandidates approximately investing to Repeated with a population investion, meeting to Repeated with the last emission.

Sentral approximition plants prechanging and known 🚥 produce jager aminsing. These include sequencial two-photon absorption apconversion, covocative many tantier ecconstrates and phoned evaluation approaches and a sequential two-phones absumdos upconvention and cooperative energy merafor upper-union are illuminated in Fig. 3 for ECYALO. Referring to the ion labelts, 'A', a plane photon at SIR are initiated the "Tays - "Iays transtion, "The "Lags made papidly extrant to the intermedials " $I_{11/2}$  state, which has a Dilations (7) of 1.2 ms. For suprendul two-photon absorption apconversion to take place the crystal mean be provided eventions. ously i hold 507 cm and 640 ms. Pures that is 940 am produces de " $I_{11/2} \rightarrow B_{3/2}$  trantition. E de 940 can flax is sufficiently high, iss tab is the "I area along will save a greater probability of absorbing a photod. that it has of minaing. The "S<sub>3/2</sub> upper just level is peopleted by mediciphonese relativities from the "Psice state to indicated in Fig. 3.

Cooperative arrange transfer approximation is leadstate by almosphere a 807 nm. If this prightering lens (A and C) arrange the  ${}^{1}$  barafer can been by a pressu divider to Auger accombination. As shown by the distant lines in Fig. 3, coopensive accepy transfer upconvention proresult ion 6 to the  ${}^{3}P_{7/2}$  side while to A address to the present state. Multiplicates relaxation from the



F(2: 7: Precisi strange book) alagaines die Bac Yoka Ca. Back george aladustiene bit die right of the worksite same includence in alargain. of the Back strate.



Ma. 3. Decembration pairings in derYALO 72 begeinteil DEphone sharquiste operacycles <sup>444</sup> conjunctive cauge pression quantypique, 'A' 201 'M' pairintet applicative jane. The solid means applicate prices, spiceles. 444 analy means represent mainfalance relatives, and the during limit believe appreciate partypip pression.

<sup>6</sup> $R_{1/2}$  sinis provision the <sup>4</sup> $J_{3/2}$  apper laser level. Genergy institier is coming subsets, generating [1] only 9.3 cm<sup>-1</sup> of encode energy. The purp efficiency for cooperative operativity is resident to the <sup>4</sup> $I_{11/2}$  fillibility, so the conjutation of two adaptioning into 57 the intermediate state and subsequited energy institier mass occur before can of the into decays.

The wavelength 300 nm and 340 mm shows is Fig. 3 explored manufaces 40 the lowest State level of the respective variable state. The mage of wavelengths in 295 nm to 300 nm for the five  ${}^{4}I_{15/2}(1)$  $\rightarrow {}^{6}I_{3/2}(n)$  manufaces, and 235 nm to 340 nm for the finan  ${}^{4}I_{11/2}(1) \rightarrow {}^{4}R_{3/2}(n)$  manufaces. All wavelengths are designed with their variants values. Laser estimates 47 550 nm membranes on the forth State level of the grants into 42 212 nm<sup>-1</sup>. This creation is the most interms of the algin  ${}^{4}S_{3/2}(1)$  $\rightarrow {}^{4}I_{10/2}$  fluctuations likes.

Sugnessial two-phonen strategies approved in pumping and ison reported [1] to produce it of W of laser comput power with an optical conversion officleacy (laser output power or a fraction of institient parap press() of 1.2%. This power was obtained with the crystal # 34 K. Approximately 193 at ¥ of parage power at 765 am was used at produce the  ${}^{4}L_{16/2} \rightarrow {}^{4}$ 1,472 transition, and 250 mW at 840 mm was mad 47 peaks the  ${}^{1}I_{11,22} \rightarrow {}^{2}P_{3,22}$  introduce. The party flux was generated using a dual warminogia Throughhis laser that produces elimpitzneous carilacion 🕫 hoft. passo wavelength. The pump laser is described in most Sevel to the literature (9,10). For concentive carry instifet pumping the apconvention laser ourper power [2] was 166 erW and the optical energysky efficiency was 17%. This performance was echieved using 975 atW of parag power # 307 am. so pusp the  ${}^{+}I_{H/2} \rightarrow {}^{+}I_{H/2}$  modules. The Br:YALO oryphi was maloreined at 34 K. The dependence of the later output on passip payor is approximately entrichette for voorsentige oneren trientifet, sonresting that optical conversion efficiencies biging days 17% can 🎮 produced with bigher perce power.

As poind obowe, phones everythe approximation is characterized by absorption or wavelengths manpict with enterising from a metasyble pict of the ion. This paper mechanism is illustrated in Fig. 4 for a detectional fast. Assessor that fee A optimizer metassible level 2. The exacts is traditioni with pump that antiques, with the  $2 \rightarrow 3$  manifold, proeasting los A 🕫 level 3. Population in level 3 cm deces to level 1, producing upconvenion emission. Alternatively the ion is level 3 one stateful part of its energy 10 originating ground 1000 inc h by cross mbastion, a process similar W concentration geneching. Cour miantium energy consist produces was ions is level 2. Since the laws) 2 bliethich is long, the two ince 🖙 sheeth udditional purity admittion as produce fear in level 2, the fear PRP produce sight, and so on, Linder convertises conditions [1]] pross releasibles, energy interfet' produces on "scalapping" of population is lovel 2.

There are 000 requirements that must be establish for ph0000 avalancing approximation range attractive. The few in that come relaxation energy attractive next be compatible with the  $3 \rightarrow 1$  crossition 2007. A large cross relaxation 500 another table outsity this condition. The energy high Rr into density help outsity this condition. The energy applications in that the  $2 \rightarrow 3$  exclusion. The energy help outsity this condition. The energy help outsity this condition. The energy applications in that the  $2 \rightarrow 3$  exclusion. This condition provided as a parage deschool for phonon



Fig. 4. Advanced expression of phases constraint opportuntion for a Semi-land los. 'A' and 'B' indices arighteding loss. Table course approach spinor constraints and the chained courses indicate oran advantative losses for two iron. The destraint course matching the start constraints. Icani 2 approach to account courses of the spo-remaint elements to the loss.

evolution operatives they. A long mither table to the filetimes and a longe absorption cross section serve to achieve the magnitude of the foreshibit pump takessity.

In was second that loss A starts out in used 2, and indeed a simil population in this lower is vequined to infrirm photon evaluation upconvention. This population is produced by cont-resonant chargetion of pump flux by isom in the ground start as illustrated in Fig. 4.

Both sequential two-photon structure encoursetion and ecoperative energy transfer upconvention. invelve option pamping from the "l<sub>ings</sub> graeod. state. The twide not flast a distinut, third pump anothaniam produces acconvention later creitation in In:YALO includes the automates of the manched proop transitions as adjusted in the  ${}^{4}$ l $_{0,c}$ menumble state as well as the substantial differences in the parametric dependence of acconvenies lane. satuloù istitad by manarable stat skavepten GMSA) compared to then produced by graned manstrateption. For estangle, the temperature dependence of the lower angout power your through a part. as 34 E when the power maximum is cooperative scorgy unusion spaceswerries [1]. On the other sand, for opconversion emission inscholing 255A die loser

anges power decreases manotonically [2] with tempersizer. The highest laser angest general sets obtained at 5.7 K, the lowest transportant produced by the crystellit. The output power was 13 pW and was produced with a power wavelength of 791.3 cm.

MSA-initiated approximation in E2: YALO is Illustrated in Fig. 3. Five wavelengths resonant with instations from the  ${}^{4}l_{13/2}$  state produce approximation in Fig. 3. Five wavelengths are 196.2 on laws steinist. These wavelengths are 796.2 on 794.4 nm, 791.3 on, 789.1 and rad 737.4 nm, and correspond to manifold from the fast fourk level of the  ${}^{2}l_{13/2}$  state to the second through the state for the  ${}^{2}l_{13/2}$  state to the second through the state form second to the  ${}^{2}l_{13/2}$  state to the second through the state form from the  ${}^{2}l_{13/2}$  state to the second through the state form from the  ${}^{2}l_{13/2}$  state wavelength to the first fourt levels of the  ${}^{2}l_{13/2}$  state produces to the low from the first levels of the  ${}^{3}l_{13/2}$  state produces to the low from the first level of the  ${}^{3}l_{13/2}$  state produces to the low from the first level of the  ${}^{3}l_{13/2}$  state produces to the low from the first level of the  ${}^{3}l_{13/2}$  state produces to the low from the first level of the  ${}^{3}l_{13/2}$  state produces to the level level of the  ${}^{3}l_{13/2}$  state produces to the level level level interaction and state state level of the  ${}^{3}l_{13/2}$  state produces to the level level level interact 50 cm contacted by parageling # 791.3 on, and the wavelength was used for most of the fusions come measurements.



Pap. 3. Opennessing in Britalio induced op successive comabanyoing full-terminary spaces spaced successive any secondlegistic sublishes a shortby and do. June Spaces over adminisher copy marker. The <sup>4</sup>1<sub>124</sub> COM is consensive.

Referring to Fig. 5, pro-resecut sheerption of the passing flux by ground white lone followed by relates for from the  $[1_{9/2}$  state populates the  $[1_{11/2}]$ metasteble size. Resonant absorption of a 791.3 and photon provident line A from the "L<sub>10/2</sub>(1) livest as the "tight of a stars. The "I 13/2 were has a lifetime [12] of 7.2 the Relations from the  $^{2}\mathrm{H}_{\mathrm{H/2}}$  state to the "83/2 state and subsequent radiative decay to the "I15/2 state produce upopaveniles parimine. Alternetimely, proveduction in the "S<sub>1/2</sub> store was predictions in care related/or energy transfer with neighboring graphic white the B lpha produce two loves in the " ${
m I}_{
m cover}$ mans. As blownadd in Fig. 5, ine (i in propagated to the "L<sub>IS/2</sub> state diracity while its A populates the " $I_{D/2}$  while by achievation from the " $I_{D/2}$  while. The mean energy produced by cross related to from the  $S_{3/2}$  while is approximately 1500 nm<sup>-1</sup>.

Attempts an illument, cross relevation from the <sup>3</sup> $H_{11/2}$  must one cross to well, in this two terms relevation energy instafer initially produces population in the <sup>4</sup> $I_{3/2}$  state (io) A) and (io) from the <sup>4</sup> $I_{3/2}$  state (io)  $I_{3/2}$  state (io) I

As treed shows, MSA-initianed unconversion in Br.Y ALO had been proviously assigned [2] to photoe. enducte paraging, indeed the Kinis processos illuscuted to Fig. 3 show soveral observes to commenwith photon evaluation. However, 4 is improved to and the population is the "L<sub>11/2</sub> and may be produced by orth cases missivities energy incoderfrom the  ${}^{4}S_{3/2}$  more and non-resonant absorption. from the ground state over through plantes, evaluation does not take plana. Rephysioking the metantakie state population is secondal for lase openuing, as the apper later level is fid by resource shourdkan of pump fut by "I<sub>EV2</sub> ions. The population inversion in the "S<sub>3/2</sub> and is metaolised in the streems of photon evaluation promptog dan to piert to the seledively time cross situation for the  $T_{cl/2} \rightarrow T_{c/2}$  eronovem absorption

Reperimental results will be processed below which contraction for association of photon assistation pumping with MSA-initianed opconversion is Bt.YALO. This is followed by a description of the stargy flow packways that produce opconversion omission.

# 4. Bandta

Two types of fluorescence measurements are beown to sensitish photon trainedto appropriate in the dependence of the approximation fluorescence on paper power. The date producest by work a meturement are filorescent echematically in Fig. 6. An low pump power the fluorescence township values quadratically, but as the paper power constance to filorence a measition point is resolved. The cases of the transition appear an described in the province transition appear an described in the province section. As the pump totescence well toward threshold pump power as described in the province section. As the pump totescence well toward threshold its spectrumine and investor apple characterized by a quadratic dependence on pump power.

The distance of a theplachi in the propy power dependence is not sufficient to take out photon enducte a the dominant sponsversion pump mortualizer. The strappent dependence of the flacese cance interview provides a definite indication of phothe system is a properties of purples. Two memory is one illustrated echemotically in Fig. 7. in Fig. 7A the iticantus is the fibotescence with time is those in the sum interv platest analasishe appartmention is agt teldas place, while Fig. 78. Ibetains the fistercaus date trajected when photos avalancie progtog occars, to the latter case the exports region of On fluorescence dependence is produced by the initici arramental grouph of population in the nationalis suits. The imparts dependence of the speculation features will extituite Fig. 78 for gang privers due privat the platest embacks fucedanid.



Phy. 6. Activately. Minimum of the Angendress of the Anternmany Willings as party power, when yourse maintain approximant Party of ances. But and the Appendiants.



Fig. 7. Scheinnis Windolms of the scapiers, depintities of the spectra-type flavorecore havetally the due case where physics indicate 2007 an acces (e4) and the case WHEN the physics indicate depinted is presented (b).

Fig. 9 above the unserved pump power dependence of the III:YALO upconversion fluorescence. The pump warelength is 791.3 nm and the crystal comparations is 7 E. A flast of daps 2 is drawn to 3100720 the approximately quedence dependence of the fluorescence initiality on pump power. The data do not indicate the prosence of a pump iterateloid. Data when using other 503A pump wavelengths gendence place similar to that shown in Fig. 8.

The second dependence of the fluorescence is Maximial in Fig. 9 the approximation produced by are different pump wavelengths. For Fig. SA the pump wavelength = 307 per and comparitive energy usular is the demission paper medianizer. For Fig. 98 the pump wavelength is 791.3 mil. Figs. 96 and 98 cath coasta two tracas the agent 2008 organ ernia the Anomacence pales while the lower wave repretents the pump palse. The fluoreassace detector pales potentity is degetive and DOF a breating approacimatchy collections with the first borbsterril grid Hos below the une of the outlingsum frame, in Fig. 9A. the financessos introdity examines rapidly alies the cluster or space and mechan structure structure  $1 - e^{-\alpha/2}$ , where + is the lifetime of the "L<sub>11/2</sub> date. The slow 600hy of the 550 nm fitternecence following pump pedia comination is duratedatic of depending asargy mass<sup>for</sup> approximation and is due to inter in the long-lived " $1_{11/2}$  save centioning to find the " $9_{3/2}$  scene.

to Fig. 98 the time required to math devely wate is longer due to the 7.2 dis lifetime of the  $^{+1}$   $_{12/2}$ note. The repid decay of the emission following termination of the 781.3 nm excitation pake infoentes duel concentive energy transfer dues hot prodore algorificant appoarcement cartarion of this pages wavelength. The count of 550 nm finemecence does not display a concerne region of the type (theorems) in Fig. 78. Data pinillar to dust alternative Fig. 09-water obtifined for pump wavelengths corresponding to trustitions to the other Stark levels of the "B<sub>11,72</sub> NWE. For all excitation wavelength for these of the of existence ADD new events constantial functions pupp power up to the mealmost pupp power available (approximately 900 mW). Clearly phones avalanche appoarremien ciezà dei ada piace.

The compared dependence of the fluoreacence of 653 van the to fix  ${}^{3}\mathbf{P}_{8/2} \rightarrow {}^{4}\mathbf{I}_{15/2}$  evanition, and at 973 nm the to fix  ${}^{4}\mathbf{I}_{11/2} \rightarrow {}^{4}\mathbf{I}_{12/2}$  massive, were also received. The bases not shuffer to the shows



Fig. 3. Variables of the 380 up problem intendsy with many prove the IntYALC, finite in draws = tailoute a single 04 2. 2014 case are implementing, and the proop providingly in initiations.



Fig. 9. Theopiesi deput/store of the 325 at appropriate Contenanne. The upper must is must contingive requisities the future come price dynamic with a planetic to the FMT probability in prove this dynamic with a planetic to the FMT probability of probability of an interaction is dynamic with the probability of probability a contribute signal with the prove is no. The three with to 2 app/site in term multiply and the prove is no. The three with to 2 app/site in term multiply and TM at the probability multiply brought is 357 and for multiply on A and TM 3 and For weight form. It

In Fig. 9A or Fig. 95 depending so whether the pump insertion originates in the  ${}^{1}l_{M/2}$  or  ${}^{2}l_{M/2}$ sittle magnetively. We also measured the temporal dependence of the flavoratomer 41.1.3 µm due to the  ${}^{1}l_{12/2} \rightarrow {}^{3}T_{12/2}$  transition. Emission was detected as ing a Co photoelistic is conjunction with an interfanece filter sourced at 1.472 µm. The FWHM of the filter was \$3 nm. For pump wavelengths restand with ground also alsoupties the temporal dependence of the 1.3 can sectuate was similar in that shows in Fig. 9A. However, to traitation at 1.5 gap could be measured when the pump wavelength was paped or with transitions from the  ${}^{3}l_{12/2}$  sitted.

Non-moment absorption by ground and  $\mathbb{R}^{3+}$ into physical properties by ground and  $\mathbb{R}^{3+}$ into physical properties in the MSA induced spectrometrics properties and the moment in the properties of the non-moment properties are in properties of the non-moment properties are in MSA lines by an amount inflations to tribulation spectrometrics fluorescence. Emission in the 970 nm. beed due to the  ${}^{2}I_{11/2} \rightarrow {}^{2}I_{21/2}$  transition was used to provide a measure of the sensingle  $\mathbb{R}^2$  the non-resonant  ${}^{*}L_{13/2} \rightarrow {}^{*}L_{p/2}$  transition illustrated in Fig. 3. Following absorption the  ${}^{*}L_{9/2}$  must relates rapidly and efficiently to the  ${}^{*}L_{11/2}$  must. Emission in 970 nm is developed on motion due subrets to upconvertion pumpling metart.

Any S-1 PMT was critically at 00° with respect to the cardinition axis and was used in one-paradon with a filter to block wavelengths shower from 930 cm. The pamp wavelength was 200 to 797.3 cm. 1.1 cm higher than the 296.3 cm MSA time and approxmately 3 cm methods from the measure ground arout manifica. Emforteen at 970 cm is shown in Fig. 10A. The slow for and full risces indicate that the signal is deministed by floorescence rates don testimed proof light. Fig. 106 shows the FMT output shutlend with a pamp wavelength of 990 cm. The purey wavelength is almost a factor of integrates further methods from the measure ground some training show the 797.3 cm maintime wavelength. As Kills use links



Phy. 10, Pharmateness produced W can exercise heatigness. But confilingions, excepter two trans. The symple trace polyheat the principle producty excepted, which produces a publicly signal, which do proop is not. The lease must separate the 700 me theorem areas. The defaults polyheight is this task is seguriter. The THEO must be such coefficients is 2 app/alm. The coefficiency gold, is increased for the Harrissence signal in (20 minutes on (AA: (A) Pharmateness of 700 me using a proop transingin of 70° 3 and the PAT signal for a proop transingth of 50° ms.



Fig. 11. Transient dependence (F die 2017-214) maankinder m. 1913 op: The crystal coppositions in 7 K and die sind W44 is 2 um/M4 The deleter patienty is patient.

970 no floorescence is observed and the detoxing signal is due shows estimate in contrasted light. Note the rapid rise and full times. The light tool in Fig. 103 was need in provide a committee for occurred light in the fluorisonnes signal.

The 970 nm contrains was also contained with the plicap wavelength senation, with the MSA manificar # 796.2 nm. For revocant contration the financiamore intensity was only 68 closes as high as the contrand furnements intensity obtained from Fig. 10. This same indexes in the son-resonant pump rate is an anomality higher in ErrYALO data is crystals for which phone avalanche upconversion from the team neofinant. For stample, phone availanche andeling adequations are a ratio for the resonant (MSA) to the non-resonant (ground sum) absorption rate coefficients of increase 5,000 and 10,000 for Nd:YLF [11,13] and NLCaCdCl<sub>3</sub> [16]. This ratio is indepention of the pump intensity.

The testigional dependence of the crystal toportaingion is 791.3 cm is shown in Fig. 11. The detroace in transmitted intensity indicates a letticity of papebalace in the  ${}^{1}L_{13/2}$  state. This detroace is consistent with the  $1 - e^{-1/2}$  time dependence of the florestacases intensity its scenario in Fig. 98.

Existence of the 700 mm was spectrally approved to detectains if the cross relations pathway involving the  ${}^{2}H_{11/2}$  scale is a significant factor in the spoorversion general. The near-momenta for cross relatresion energy provide involving the  ${}^{2}H_{11/2}$  mass anggrap that the bracewing ratio for this pathway may



Fig. 12. For more an UPACE to Extrately at 7 K. (a) there is about a thread with an embryour different with an edite (B) down within the embryour  $\Psi$  75%, where the exclusion level H is the instant of the light the  ${}^{3}P_{3/2}(1) \rightarrow {}^{3}L_{3/2}(n)$  and the  ${}^{3}S_{3/2}(1) \rightarrow {}^{3}L_{3/2}(n)$  manifolds. The conduction is the instant of the light the formula  ${}^{3}P_{3/2}(1) \rightarrow {}^{3}L_{3/2}(n)$  and the state of  ${}^{3}S_{3/2}(1) \rightarrow {}^{3}L_{3/2}(n)$  manifolds is the order of the instant of the state of the state

to higher than would atherwise to acquarant. Although the hyper state tilletime is short, the pump flat populates the  ${}^{2}E_{11/2}$  state directly. A high pump photon density might provide a sufficient measity state population in this level, holded, the flat that we 1.5  $\mu$ m radiation is observed when the pump wavelength is retained with true of the MSA mentitions is constituent with a high MSA promp ster.

We attempted to use floorences from the  ${}^{+}\mathrm{H}_{11/2}$ and to describe whether a memorable population to this level is maintained when the pump waveimpth is retained with one of the MSA manddom. Berlanian from the "Harry state is generally seak, and the fluorenceurs spaceture was firm minor as rocen, temperature to identify to emistion fine that could be ated to recultive the <sup>2</sup>H<sub>11/2</sub> population. The 700 cm<sup>-1</sup> surgey gap between the "\$3/2 mill and <sup>2</sup>H<sub>11/2</sub> some allows a returbudy high thereast population in the latter state as soons comparatore under succession coordinieus d'al produce a succes alla popalation in the "91/2 state. A actual fluorescence pask of Y22.1 nm, was characted when the toold relationstime Br:YALO crystial man excited at 207 and. This wavelength corresponds to the  ${}^{2}\Pi_{11/2}(1) \rightarrow {}^{4}I_{13/2}(4)$ condition. The crystal was control to 7 K and excited with paper cadantes in the 800 am band. Poor wavelengthe retained with white ground state or representative plates abarterplations where used, item are 5229.] em enjution and characted it this testamoniate.

In the course of searching for low level fluorescases from the  ${}^{2}H_{11/3}$  state on denoted operatortion fluorescence that to the  ${}^{3}P_{3/2} \rightarrow {}^{4}I_{9/2}$  baseline. The  ${}^{2}P_{3/2}$  (1) level is at 31 449 cm<sup>-1</sup> and five emission lines are produced state 530 nm. Endedon. Here the  ${}^{2}P_{3/2}$  state was obtained with a pupp wavelength of 207 and ion are for the MSA pupp wavelength at 790,2 and. The intensity of the 530 are fluorescence is more than 700 optics of registrate balance the 530 cm emission from the  ${}^{4}S_{3/2}$  state. The fluorescence type: an above it of fig. 12.

#### 5. Distanciona

# 5.1. Mechanism for MSA-builded appreciation

The fluorogeners data indicate that a conclusion other than platters containing produces up-



Fig. 13. Placester involved in MIA initiated spreammitte in a first-lovel with 4, and 4, repetited alternities, 2, and 2, repetited single its datasy pressure love practs 2 and 3, sequetrialy, and do datasy line initiate error extension.

convertion emission in Br.YALO. Non-recount asquantial rwo-photon absorption upconversion is consimor with MSA-initiast pamping and is illustrated in Fig. 13 the a time level ion. The crystal is promited at a weightenet retained. with the 2-63 mention. Non-assamt stompton by ground ann ives gapelees level 2 440 a page rate coofficient of  $R_{1}$ , and leass in level 2 are promoted to appar base lavel 3 with CONTROLOGY Ry. How-recover asquandat revo-phoson shearpalen is exercises [6] is manoprecision Shar Islam. For times latent room intepergénes operation pérgèdes à duistation de 1000-1996 alcorption we due je the american brand steaming firms. Although the non-resonant Mintition rate is statively large in Br.YALO, this rate is only a small fraction of the schoold, aboundoe rate. in is therefore wellkely the Jean underline could be associated by non-resonant acquirated revo-photon abtarpilan anoming signs.

**Economic in ReYALO the mechanics shift papebation produced by non-resonant acquirities two-phenic algorithm is exclusived by contribution, that to errors relaxation energy counties. Cross relevation is a gets mechanical energy counties. Cross relevation is a gets mechanical energy counties interaction incomable shifts for such category counties interaction havelying an excited filewel 3) ion. It is likely that both of these pump conductives operate situations make an produce the <sup>4</sup>S\_{1/2} state population sufficient to reduce have evolution.** 

EcYALO is used at the one-restricts absorption FID conflicted R<sub>1</sub> is not negligible teledue to the resonant description rate coefficient  $R_2$ . This is and even R cryogenic temperatures and ramits from the proximity of the  ${}^{4}I_{10/2} \rightarrow {}^{4}L_{1/2}$  and  ${}^{4}I_{10/2} \rightarrow {}^{2}H_{11/2}$  transition wavelengths. Recently, Breaker and Jundye [15] modulet specieversize in ErrYALO. Their moduli is combined update experimental observations reported in this work, and indicent loss the effect of increasing the pump threshold too photon avalanche. When the rate of  $R_2/R_1$  is less that 10, photon avalanche upconversion may not necur at any pump power level.

For some temperature exception in EntYALO propied with 635 mW of laser power m 795.2 cm, Breather and horize prod.  $R_2/R_1 = 2$  and calculated the fractions of  $B_{3/X}$  population produced by correrelative and non-resonant expectively. The relative completion of the non-resonant strategies rule is consistent with published areas reations for EntYALO [16] and EntYLP [17]

The proposed upconversion pump such that is respecting or "troping" of contains between the upper laser level for, abcomplively, the  ${}^{3}H_{11/2}$ state) and the metastable state. Chan relaxation from the upper level produces tous in the  ${}^{4}L_{12/2}$  some while subsequent shareplion of pump photons capapuluum the upper level. Loop gain reach from the production of one statestable state, inc. by mean relaxation interview to for it the upper level and one in the gaptered mate, and loss is produced by upperversion endowich from the upper level and one version endowich from the upper level and the gaptered state. Additional population to the statestable state is produced by con-measurem ground state absources.

Looping through the universe chaonal and heart channeed in relation to the 2.8 perce  ${}^{4}I_{11/2} \rightarrow {}^{4}I_{22/2}$ Br least theoretical [18]. The 2.8 percent is produced by optical parameters at 800 and to populate the  ${}^{4}I_{9/2}$ states. As acted above, this state relates to the  ${}^{4}I_{12/2}$ opper large level. As an absentiative to relateston, as has in the  ${}^{4}I_{9/2}$  state can produce root leves in the  ${}^{4}I_{12/2}$  terminal large level by core relateston between root in state low. Comparison extraordion between root is state low. Comparison upconvention between root is the  ${}^{4}I_{13/2}$  state impopulates the  ${}^{4}I_{1/2}$ state. The looping mechanism is the 2.8 percent latter computer prove retenation to the lower level fellowed by cooperative upconvention to the upperlevel. This looping model is consistent with the observation of higher level efficiency using a larger peop verselength to exclus the  ${}^{4}I_{11/2}$  suce directly (~ 970 em), stack in 2000 case the terminal level level is not populated by trass relaxation from the  ${}^{1}I_{0/2}$  state. It is consistent as well with the observation of the lenger block of the neuroinst level relative to the " $I_{11/2}$  appear level level. Classically such symptometical level relative to the " $I_{11/2}$  appear level level. Classically such symptometical level at the symptometric level of the neuroinst level relative to the " $I_{11/2}$  appear level level. Classically such symptometric level (18) opened as at bottom in attactive lifetime of the " $I_{11/2}$  state.

Looping his also bent discussed [21] to deall for systems that waterge only nonpesative energy Demfor-operative in this model damy from the upper level to the matartable level excase by a cascade involving both multipleneon relatedon and cafasive solution. Cooperative upcontention involving jum in the matartable level re-populates the upper level, completing the causy loop. Looping in these by the sucharm [21] to result in anisoted quenum efficiency as well as counting cartain cancient effects in the lever output.

No printing was been as support significant participation of the  ${}^{2}H_{11/2}$  which is the prove relatation tailing transfer pathway. The experimental remate was constrained in excellent for  ${}^{2}H_{11/2}$ population in weak. The energy measures of the initial and final more involved in cross minimized from the  ${}^{2}H_{11/2}$  while complet with the observation from the  ${}^{2}H_{11/2}$  while complet with the observation that the  ${}^{2}H_{11/2}$  while is the reconnect level for the optimal paper bunction, support the participation of this generating pathway. It is of journal in core that both scatted state statespilles [17] and cross miniation [16] involving the shore-livet [26]  ${}^{4}L_{1/2}$  manwas reported to contribute to the spectration pump dynamics to Be-deput crystals.

A previous assaury [2] to decomine whether the <sup>1</sup>H<sub>11/2</sub> task participates in coses relatation was also beenchoose. In that measurement exclusion to 647 refs and part in an effort to pump the  ${}^{2}L_{13/2}(1) \rightarrow {}^{4}S_{3/2}(1)$  condition. If approximation particle  $L_{13/2}(1) \rightarrow {}^{4}S_{3/2}(1)$  condition. If approximation particles and basis observed the energy meaning parts particles up involving the  ${}^{2}H_{11/2}$  state could be eliminated. However, an effectiveness an end by detected in tight of the detariation of the MSA-initiated pump methodom described above, it can be recognized and the failure of ptimp light at 847 aim 76 produce operatorsion say be a reflection of the substantially lower non-conrant elementity suggest due the  ${}^{4}S_{3/2}$  state is an invitival in arous relevation. The ann-resonant absorption cross section varies [17] as  $\exp(-\alpha\Delta E)$ , where  $\alpha$  is a evolution of  $\Delta E$  represents the energy difference between the pump photon and the reserve ground state matrixities. For a pump cavalangh of 257 and the energy difference is approximately 500 cm<sup>-1</sup> compared to two of cm<sup>-1</sup> for the MSA lines run 205 app.

# 5.2. The rule of corrys recycling in comparation space-astrian probains

Cross relaxation from the  ${}^{5}S_{3/2}$  state is so differlive energy transfer mechanism. Concentration quinching was reported [22] to reduce the framecrace lifetices of the  ${}^{5}S_{3/2}$  state in a 1.5% depail Br:YALO crystel to 50 ps from the low concentration lifetices of 160 ps. Annet and Chars [) 7] inditrop that the spannetimet ( $n_{1} = 1$ ) trans elements rate coefficient for Er:YLF is 5 × 10<sup>6</sup> s<sup>-1</sup>.

Although efficient cross relaction is important for MSA-initiated spectromation, it is a tors spectramins for cooperative energy vacation operation. When the Er.S ALD mytest is percepted [1] by wavelengths restored with consistent from the ground star, cooperative energy touchly pumping densitives the operative energy touchly pumping densitives energy vacation dynamics. Recall that cooperative energy vacation operation requires two is the  ${}^{4}I_{11/2}$  state to produce to los in the  ${}^{4}S_{2/2}$  state. Cross relevance recovers population from the  ${}^{4}S_{3/2}$ may go theorem required to produce a visible photon.

Despite apper later level populated loss by cristrelation, cooperative energy transfer pumping in first ALC has produced the highest optical convetion stitutionary reported for an optical convetion stitutionary reported for an optical convertion stitution produces reside much of the  $S_{3/2}$ state leads courgy within the pump dynamics loop, allowing the apper later level is to re-papalated. Exclusion is respected by cooperative optical courlevelying the quanching produces.

Questioning letterly produces us too in the "L\_{11/2} many and app in the "L\_{11/2} man. The its is the "L\_{11/2}

state our participate in cooperative energy taunday with a seighboring lots in the "I<sub>11/2</sub> state to repopulate the "B3/2 state. Alternatively, the lot can doing to the "Inte state. If the "Inte schedule, the 111/1 state can be re-populated by cooperative enstar toucht with mather wh in the Jour state. Cooperative energy organizit operation betwoeld adighiboring loss in the "J<sub>D-72</sub> state is efficient in Br-depoil crystalls, and 5 was reported [20] that this energy opposite granus determines the population investigate biophysics of the  $\mathbf{Er}^{\mathbf{1}+\mathbf{1}}\mathbf{1}_{11/2} \rightarrow \mathbf{1}_{11/2}$  2.8 are low renation. Alternatively, these loss in the T<sub>15/2</sub> state can participate in a "telo" operatoredou process in predoce an lot in die "S1/2 state directly. 2015kud 550 ma kwa antuko ka bata dapoextend [23] to for YLP using the opconversion pumpարը առեւ 55 թ.ա.,

If the cross relevation-produced ion is the  $1_{11/2}$ state endergate a second cooperative energy touster interaction to re-populate the "Says more, the reduction in pamp pointing efficiency may be as lists as 114. To ma this, rote that in the dimense of cross relaxities are 600 are plantas de rejeitad la predage 🕶 ion io de "S<sub>345</sub> gran, Whith cross relaxition constraints, a third primp photons to exceed to re-propulsing the "E<sub>set</sub> shap. The third photos primeres a proceed state life to the "L<sub>al/2</sub> state. In this case there passa phonone pipeluos au los le die <sup>4</sup>6<sub>3/2</sub> state plus care ion in the "Imer store. Based on the tolo presses, the in the "Lings represent one-mint of the speece repetinged to produce associate ion in the "S<sub>3/2</sub> lows. For this process their, there pump photons position  $1_{5}$ toes in the "S<sub>3/2</sub> state and the galaxies been in 11%. nited ve to the question for contailor pathway. Emilarly we can calculate the potention ives for other performing for reprinting the "Same star, These lowers onge up to 33% to fong in whiter cours algoritor-produced ion relative back to the "L<sub>int</sub>s ground state, Recycling Systerics, have been discontrol in petvices papers [15,20,21] on Br-depted be a

Having discrimination the solices of crust valuation on princing the efficiency of cooperative energy transfer-operators promping, we note that cooperative energy transfer invaluing ions in the <sup>4</sup>1<sub>072</sub> state represents a ions antidemitte, for the WSA-initiated pump process discriminal to fraction 5.1. Population in the <sup>4</sup>1<sub>1372</sub> meansable state in antidated <sup>30</sup> scatter spectromion, which perceptions wavelength is resonant with transitions from this gam. To the scoret that compositive energy transfer depictes the flatamentic main provincion, the going efficiency will be ufound. This reduction is analogous to that described above in the minimized parap photons, we required to penduce a visible photon, although in this case is in due to instan symplecture.

Coly a solid reduction in the efficiency of MSAinference operations is supervise to result from compositive energy transfer. This is doe to the lower steady state density of  ${}^{2}I_{12/2}$  irons relative to the case where comparative energy transfer dominance the up nonversion pamp dynamics. The lower metistable state dynamic was domonstrated by the 1.5  $\mu$ m mitisian experiment expanded shore. The optical flat and for bSA-inference proping is rescaled with the  ${}^{1}I_{12/2} \rightarrow {}^{2}H_{13/2}$  transition and effectively righted the mady state metistable population.

# 5.1 Cooperative energy transfer particles of the ${}^2P_{\rm A/2}$ state

The appendice of the  ${}^{2}P_{3/2} \rightarrow {}^{4}L_{3/2}$  maintain lines produced by excitation at 807 are 000 ort at 796.2 ore is an observation population dynamics of the  ${}^{2}P_{3/2}$  state. Since both pump wavelengths papeinto the  ${}^{2}R_{3/2}$  state is in 80% likely that compressive energy transfer between neighboring  ${}^{4}R_{3/2}$  ions produces the  ${}^{2}P_{3/2}$  state. The most significant diffusions in the tark state populations between the energy transfer patronys successed with the two pump wavelengths is the populations between the energy transfer patronys successed with the two pump wavelengths is the population in the  ${}^{4}I_{12/2}$  state. As read, the resonable state ice density is depleted ander MSA-labitand periping compared to coopussive energy transfer paraging.

This receptative option between unline in the  ${}^{1}S_{3/2}$  plate and two in the  ${}^{2}S_{3/2}$  state at the most filely packway for populating the  ${}^{2}P_{3/2}$  state, as most other approximation pathways out be stability eliminated. For complete cooperative approximation involving lass in some that the above the  ${}^{2}S_{3/2}$  state is unlikely due to the shore lifetimes of these levels. For the longers lived groups those the tiletaw of the  ${}^{2}P_{3/2}$  state [2] is 1.2 as in Br.YALO, while the fiftitizes of the  ${}^{2}G_{3/2}$  state lifetimes of the  ${}^{2}G_{3/2}$  state [24] are 7 as and 9 as, respectively. Cooperative

carry transfer among into in the  ${}^{\rm th}{\rm m}_{\rm H2}$  such would require that five acigbboring methodolic state into participate to produce on its in the  ${}^{2}P_{1/2}$  state. Concentry encouranties from the "I<sub>11/2</sub> state in also aniliarly as that anighboring loss in that state would have to pericipate. Alternatively, allo apponversion can oncer aroung a "A<sub>1/2</sub> such the and two In the "I<sub>11/2</sub> state. However, this pathway is less likely that it's open vention involving "I13.77 state itada. The "Julya atom inferime is shower, and 7900 cm<sup>-1</sup> of additional caces energy is produced by this process. In addition, if this processy were effective it minite the expected an produce "P<sub>2/2</sub> probation when puessions at 796.2 and at well us 4 \$07 and. Tria uppersection from the  ${}^{+}P_{\gamma/2}$  state could also predate the "Pers and. This is unlikely the to the 19 pe likebra [7] of this same unwell in the later excess everyy that would be produced. The rewers, absolute level that could be populated in the  $^{*}D_{3/2}$ state, which fins [25] alcount 7000 ors<sup>-1</sup> tower in encerny'.

Dependention from the "Pays state has also black observed in Er.YLP. Basistion # 870 and is doe 🕫 the  ${}^{3}P_{3/2} \rightarrow {}^{4}I_{11/2}$  transition. It was proposed [26] the pojulation of the  ${}^{2}P_{J/2}$  state course vie a mobil map uppersysteles parage excitentaries in the first state, two orighboring tous in the "J<sub>11/2</sub> state penduce the \*S3/3 Halls by comparative energy together upcommealon. The should step comprises compositive opeonmention between an irm to the "S<sub>3/2</sub> state and one in the "Feet same. This machined up is feat likely to actor to BrYALO and the Areaford Information eménoires augurinted above for two reasons. First, the two scores juokalies in the propagal appointation incritions, the  ${}^{+}l_{11/2}$  and  ${}^{+}E_{3/2}$ , here eigenformedy abores lifetimes dans the "1,1/3 and "S1/3 states. toward webs. The lifetimes of the four score are 1.2 ere, 19 µm. 7.2 we and 160 µm. respectively. Openant, if the proposed machinelism down?00001 the population kinetics of the  ${}^2\mathsf{P}_{3/2}$  state upconvertice existing would be produced white pumping at 796.2 cm 🖛 well as IT 807 and This is not characted.

#### j, Geography part constantant

Upcannendan flacorsonner injähel V7 absorption frem the <sup>1</sup>0<sub>1/2</sub> restabilitie tate has bade risionaliteical in ErtYALC. Penge wavelengthe pred areas 796.2 nes, 794.4 nm, 791.3 nm, 789.1 nm and 797.4 nm. The data segment that the species reason pump mechanism involves took creas substation seningy standar 404 nm-resonant sequential two-photon shsception. This mechanism is somework similar to photon systemche species endowed stratight to photon systemche species endowed a sequential standardial by minimized high too-resonant greated standardial by the scientified with producing species on lines proviously identified with producing species version take antionion is a crystation line.

Copy relation energy tracely wat discussed in terms of in lagrant on the efficiency of cooperative energy matter spectroendoe pumping. The role of energy recycling is subjecting the pump efficiency lawses was described. The pathways the upconversion pumping of the  ${}^{3}P_{3/2}$  state in Br:YALO were also discussed. The inner likely pump mechanism is triorecognizive energy standar involving raw loss.<sup>10</sup> the  ${}^{3}I_{13/2}$  state and m in the  ${}^{3}S_{3/2}$  state.

### Acknowledgements

This work was appared in per. by the Office of Neval Responds. The guilton without to think Dr. Millets Kolos of Union Catbide for providing the fir. YALO crystal.

#### References

- B. Sainge, W20 J. Question Review. 30 (1994) 2814.
- [3] E. Szinge, SSEL1. Quoteen Eleview. 31 (1953) 201.

- [5] R. Bruke, E. Hammers, J. Souther, E. Hyper and R. Link, Appl. Phys. Lett. 63 (1990) 2080.
- [4] R.F. Span, P. Shee, R.S.P. Chang and R. Shu, Dyr. Lett. 13 (1993) 113.
- [3] A.L. Silvanskin, V. Lobyis and K.M. Mechanina, Appl. Phys. Lett. 41 (1967) 1627.
- [4] R. Sconge, Progr. Question. Electron. 20 (1995) 271.
- [3] M.L. Wilson, Phys. Rev. B 81 (1993) 54.
- [4] V.L. Brains and A.A. Serings, J. Chem. Phys. 37 (1971) 4717.
- [9] R. Schape and J.P. Myser, USSE Photonics Tech. Last. 4 (1982) 1.
- [19] R. Sahar and J.P. Myon. W20 J. Quantum Electron. 20 (1994) 1050
- [11] M.F. Jaches, J. Day and R. Jooghin, Phys. Rev. B 45 (1973) 10221.
- [23] K.A. Beyer, I.L. Chane, L.K. Brite, V.J., Hong and V.P. Koopen, 1933 I. Quantum Review. M (1953) 2505.
- (13) V. Laugh and R.M. Mechanist, J. Louis. 45 (1999) 545.
- [14] C. Carther, M.J. Riley, P.S. May 224 (A.V. Okolo, J. Lords, 35 (1992) 261.
- [5] A. Rowgier and A.M. Lindge. Phys. Rev. B, to be published.
- [14] M. Parines, K. Restman, and G. Hahm, Appl. Phys. A 54
- (19)2) 408.
- [17] P. Avaid and Y. Chao, J. Lemin, 43 (1920) 45.
- [10] K.C. Berammi and J. Burstein, Cyc. Lett. 17 (1982) Mill.
   [19] J.T. Wanjagen, Lanc. Historica Obschlar-Kall. Replaced CH78, 1931) pp. 165–171.
- [20] K.A. Patinek and R.R. Chang, Opt. Quantum Electron, 22 (1990) 375.
- [21] P. Marazzi S.Z. Band, J. Cot. Rev. Ann. B. 11 (1990) 101-
- [10] M.1. Wane, M. Beis, T.B. Verlahme and O.P. Mas, (1998). Quantum Electron. 9 (1992) 1070.
- [20] P. Kim and K.C. Kenil, Opt. Ltd., 17 (1992) 1199, 1923.
- [24] C. U. Y. Goyes, C. Lindele, R. Minneargé and M.U. Bulane, Opt. Soc. Aca. Proc. Adv. Belid State Lances. 53 (1992) 91.
- [21] C.M. Breau and B.M. Crossellue, Appl. Opt. 3 (1999) 275.
- [26] T. Harbert, R. Warnstein, W. Linia and K.M. Mecheines. Appl. Phys. Lett. 57 (1998) 1727.