united nations
educational, scientific
and cultural
organization

international atomic
energy agency

the
abdus salam
international centre for theoretical physics

Winter College on Optics and Photonics
7 - 25 February 2000

1218-8

"Low-Power Short Wavelength Coherent Sources: Technologies & Applications"

D.B. OSTROWSKY
Lab. Phys. de la Matière Condensée
Université de Nice
France

LOW-POWER SHORT WAVELENGTH COHERENT SOURCES: TECHNOLOGIES AND APPLICATIONS

D.B. Ostrowsky

Laboratoire de Physique de la Matière Condensée
Université de Nice-Sophia-Antipolis
Parc Valrose
06108 Nice Cedex 2, France

INTRODUCTION

The object of this course is to attempt to compare three techniques that currently appear to be the most promising for the realization of relatively short wavelength visible coherent light sources furnishing a few tens of milliwatts: parametric conversion via sum-frequency generation, rare-earth doped fiber upconversion lasers, and, short wavelength diode lasers. The course will essentially concentrate on the two latter types of devices since the parametric devices have been extensively described in other courses at this school. In any case, it should be emphasized that all three techniques will no doubt prove to be viable for certain applications. The comparison will not result in a "winner take all" situation. In order to emphasize this we will begin by mentionning some of the motivations for the development of such sources. This will enable us to understand the different constraints various applications will impose. We will then describe each technique in turn and determine the type of performance each can be expected to provide. We will conclude with a description of some interesting applications using the techniques and short-wavelength sources that have been described.

APPLICATIONS OF SHORT-WAVELENGTH SOURCES

In this course we shall define "short-wavelength" as wavelengths below those currently produced by continuous wave diode lasers, i.e. essentially wavelengths in the green to violet portions of the visible spectrum. The applications for coherent sources in this range can be, somewhat arbitrarily, grouped into three major classes: data storage and printing, display, and scientific instrumentation. Among these applications, data storage is currently the most important economic motor for device development and we will, therefore, examine it in somewhat more detail than the others.

It is clear that data storage will be the main consumer application for short wavelength lasers in the forseeable future. Currently, on the order of 150 million diode lasers are sold each year for this purpose - at an average price on the order of 1$ per laser! With the red diode lasers already being used in commercial Digital Video Disks (DVD's) one attains a 4 GB per face capacity, and a demonstrated possibility of using four levels for an overall 16 GB capacity. This improvment over the current 650 MB CD-ROM disk we know and love is attained through a reduction by 2.2 in the interline spacing - now down to around 0.8 microns, close to the finest lines used in microprocessors, and a factor of 2 in spot size due to better quality optics and a slightly shorter laser wavlength. However, only a small advantage has been gained by the passage from the 780 to 640 nanometer diode lasers, the rest has been achieved by improved coding. So, the race is on to fabricate diode lasers in the 400 nm range, with excellent beam quality, that would permit tripling or quadrupling the capacity to the 15 GB/face range. For this application it is difficult to imagine other sources being cost effective but, since the laser currently only represents a few per cent of the entire device fabrication cost, an enabling technology, such as fiber lasers, or the frequency doubling of existant high power near-IR diode lasers, could probably compete if they offer superior performance, and attain fabrication costs of under 10 $. However, whether this will be possible remains to be seen.

Displays are currently an essentially non-existant market for coherent sources, but one that has enormous potential for mass dvelopment if the enabling technologies are developped. These technologies include both the three color laser sources and adequate scanning technology, or high brightness LED arrays. On a much more pedestrian level, GaN LED's are being proposed for many more immediate applications, the paradigm being traffic lights, where good energy efficiency and long life are primordial. However, this is an application field we shall not address.

The other field of applications we will address is scientific instrumentation. These are often based on fluorescence techniques, which, using short wavelength sources, has always had many scientific and technological applications. In this course we shall describe three such applcations, quite arbitrarily chosen, as examples of the use of various phenomena and devices that shall be described in the paper. These are genetic identification, a fiber optic temperature sensor, and, waveguide examination.

Having briefly outlined some potential applications of interest, we will now go on to describe the three most promising types of low-power short wavelength coherent sources: upconversion fiber lasers, short wavelength diode lasers, and frequency doubled near IR diode lasers.

UPCONVERSION FIBER LASERS

Introduction to fiber lasers

Actually, the advantages of a doped fiber structure for the realization af amplifiers and lasers was recognized and demonstrated by Snitzer as early as 1961[1] in work that probably began before the demonstration of the first laser by Maiman in 1960. With the maturing of laser technology, resulting in the availability of a variety of "classical" laser sources for pumps, optical fibers became a remarkable medium for the fabrication of a new class of lasers: the laser pumped fiber lasers. The essential advantage of fiber lasers is that of "plumbing" i.e. the fiber allows the confinement of a high density of pump and laser powers over distances impossible to attain with bulk optics. The advantages of this configuration, highly schematically shown in the following figure, are numerous.

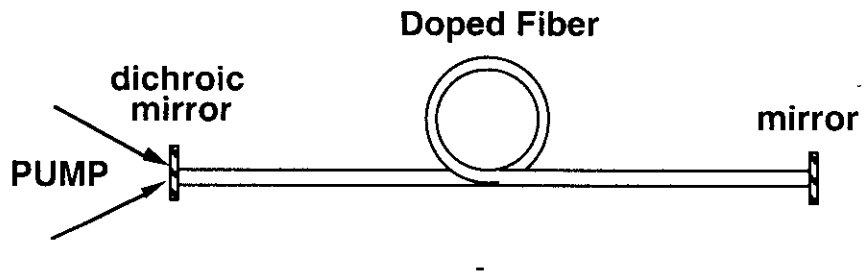


Figure 1 Grossly simplified schematic of a fiber laser

The essential point to note is that this configuration, in contrast to the bulk laser configuration, allows an independant choice of the pump spot size and the interaction length. This allows several orders of magnitude higher pump power concentration with correspondingly lower thresholds. Furthermore, since essentially no optical power is lost over the relatively short fiber lengths (a few centimeters to a few 10's of meters) usually used in fiber lasers, the doping concentration can be optimized for each desired phenomenon by properly adjusting the length. It is all of these degrees of freedom that have permitted the development of a variety of "standard" fiber lasers and amplifiers in both three-level and four level atomic systems[2]. By standard, we mean lasers that are pumped by wavelengths that are shorter than their lasing wavelength. In the following we shall be concerned with upconversion lasers, i.e. those that are pumped with wavelengths longer than their lasing wavelength. All of the previous advantages cited continue to apply but the phenomena involved in the excitation process are somewhat more complicated. We will outline these processses in the following sections.

Introduction to upconversion

In the early 1960's, before the advent of visible Light Emitting Diodes (LED's) and efficient semiconductor photodetectors in the infrared, there was a major interest in the incoherent upconversion of IR light for both displays and IR detection.

In part due to a suggestion by Bloembergen[3] for an infrared quantum counter (IRQC) based on what we would now call Excited State Absorption (ESA), a considerable amount of work was carried out in this direction over the following decades.

A number of upconversion processes identified at that time and their respective pump power density normalized efficiencies [4] are shown on the following figure.

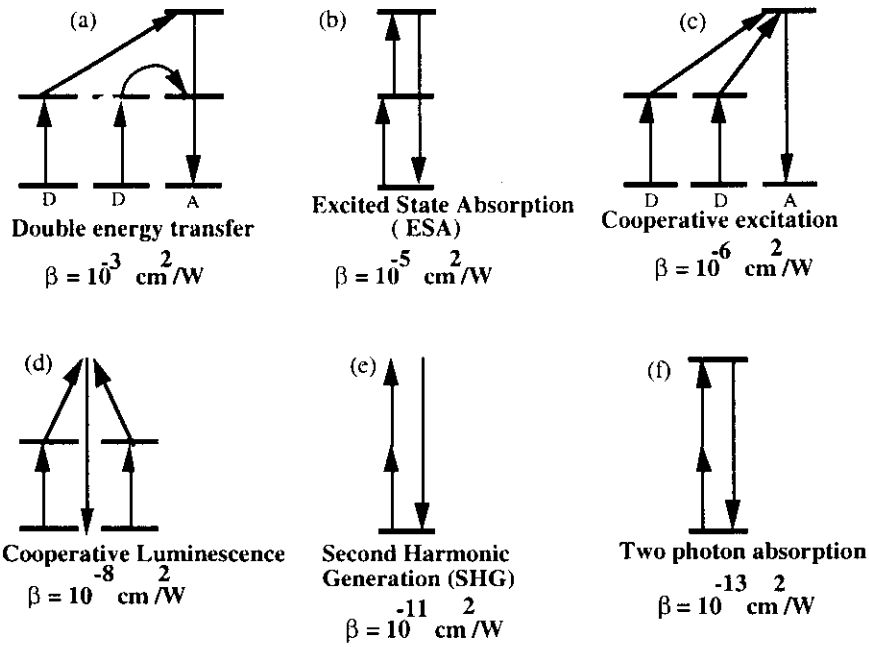


Figure 2 Upconversion processes and a rough estimate of their power density normalized efficiencies per pump power density following Kushida and Tamatani, and Auzel.

These normalized efficiencies were defined as $\beta = \frac{\eta}{P_p / S}$ where $\eta = P_e / P_p$ and P_e is the high frequency power, and S the interaction surface, were essentially estimated from experimental data on bulk samples, available around 1970 by the authors of reference 10, without taking into account the sample lengths. What was surprising to many people was the extremely high relative efficiency of the double energy transfer processes, as first pointed out by Auzel[5]. Being French, he called this process Addition de Photons par Transfert d'Energie and both the acronym APTE, and the name Auzel effect, were extensively used in the literature over the following years. Today, energy transfer is the commonly used name for this process.

The atomic, as opposed to dielectric, phenomena most highly investigated were ESA and energy transfer processes in which several ions were involved. In both cases the active materials of predilection were Rare Earth (RE) ions in various hosts. While the original motivations for upconversion of that ancient era have been adequately addressed by other techniques, the scientific work has proven to be invaluable with the advent of guided wave optics, leading to the [redacted] fiber amplifiers, lasers, and sensors that are of current active interest.

Since the performance of many of these devices is based on the particularities of the RE ions we will summarize the essential spectroscopic aspects of these ions before outlining some pertinent examples of the actual upconversion processes. .

Rare earth ion spectra

The rare earths play an extremely important role as active elements in the optical region of the spectra. Since they are the essential actors in the atomic upconversion scenarios we will develop, we present here a brief outline of their key properties.

The essential characteristics of these ions in various hosts consist of a multitude of relatively fine absorption and emision lines. This is due to the fact that the optically active electrons in the partially filled 4f shell are inside the filled $5s^2$ and $5p^6$ shells as indicated heuristically on the following figure.

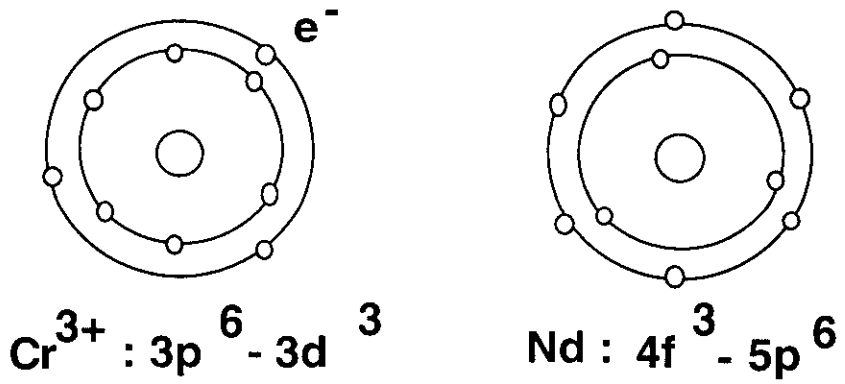


Figure 3. Highly imaginative heuristic schematization of the outer orbitales of Cr^{3+} and Nd^{3+}.

They are, therefore, partially fielded from the fields in the their immediate environment and their emission and absorption lines are an order of magnitude finer than those of transition metal ions, for example as can be seen on the following figure.

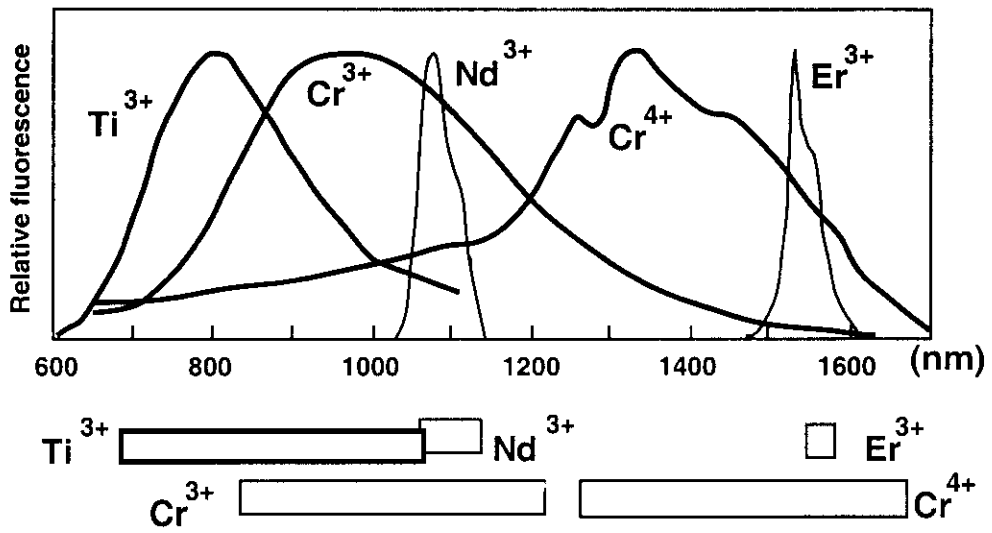


Figure 4. Fluorescence bands of transition metals (Ti, Cr) and rare-earth (Nd, Er) ions.

These emission and absorption lines arise from transitions between the levels in the ground states of the elements in their stable +3 ionisation state. These levels are conventionally labelled as $^{2S+1}L_J$ where S, L, and J represent the spin quantum number, the orbital angular momentum quantum number, and, the total angular momentum quantum number respectively. The orbital angular momentum quantum number L is historically designated by the letters S,P,D,F,G,H,I,...which correspond to L= 0,1,2,3,4,5,6,7.... respectively. Within a given LSJ level the local field raises the 2J+1 degeneracy leading to a number of Stark levels, which depends on the symmetry properties of the field as well as J. Even more important is the fact that the field breaks the inversion symmetry of the ion's environment which permits transitions between levels that would have been parity forbidden in a symmetric field. The relative weakness of the oscillator strengths for such transitions partially accounts for the metastabilty of many of the levels.

In a typical rare earth the levels will consist of LSJ manifolds having a total width on the order of several hundred cm^{-1} sparated from one another by several thousand cm^{-1}, with a typical pair being shown in the following figure.

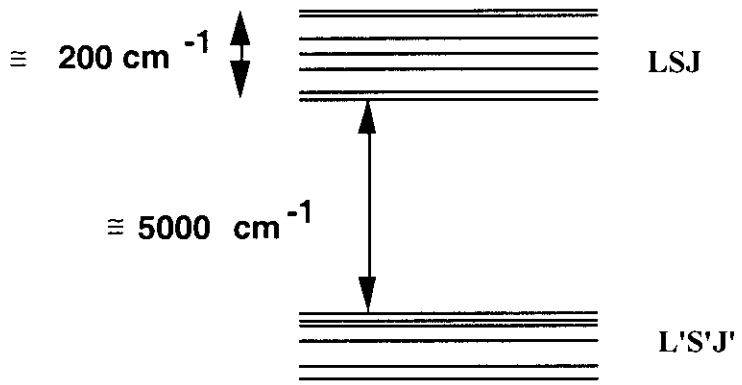


Figure 5. Energy level for two LSJ manifolds of a rare-earth ion in a crystal field. Each manifold is split into various Stark levels

It is important to note that the splitting of the individual manifolds is on the order of kT at 300°K, which corresponds to 210 cm^{-1}. This means that these levels will rapidly thermalize among themselves allowing us to consider the manifold as a single homogeneous band. It is this rapid thermalization that depopulates the upper Stark levels of the $^4I_{15/2}$ level of Er permitting the 1.48 μm pumping of the ubiquitous 1.54 μm amplifier. This rapid thermalization process will also serve as the basis for a temperature sensor we shall describe later.

A last preliminary, but essential, subject to be treated before entering the discussion of the excitation processes themselves, are the phonon spectra associated with the possible host materials. This will be outlined in the following section.

Role of the host material phonon spectra

When rare earths are used to dope a given material, the excitation process, and hence the useful lasing levels, will depend on an essential material parameter: the material's phonon spectrum. In order to demonstrate this we will begin by discussing the system that currently appears to be the most promising for the realisation of a blue fiber laser: thullium doped ZBLAN fiber. ZBLAN is an acronym for ZrF_4 - BaF_2 - LaF_3 - AlF_3 - NaF, a glass almost accidentally discovered at the University of Rennes in 1974 [6]. While silica fibers have led to very performant lasers in the infrared and near infrared, it is the ZBLAN fibers that have permitted the realization of most of the upconversion based visible lasers. The reason for this lies in the phonon spectrum of the two materials. ZBLAN, a so-called "soft" glass, has a much lower average phonon energy than silica. As a result, if a rare-earth LSJ manifold is less than about 4500 cm^{-1} above the next lower energy, manifold, in a silica host, non-radiative phonon emission processes can depopulate the upper manifold. For the ZBLAN host the the limiting energy separation neeeded to avoid this is only about 3000 cm^{-1}. This is evident from the multiphoton decay rate versus energy gap figure shown in the following figure[7]..

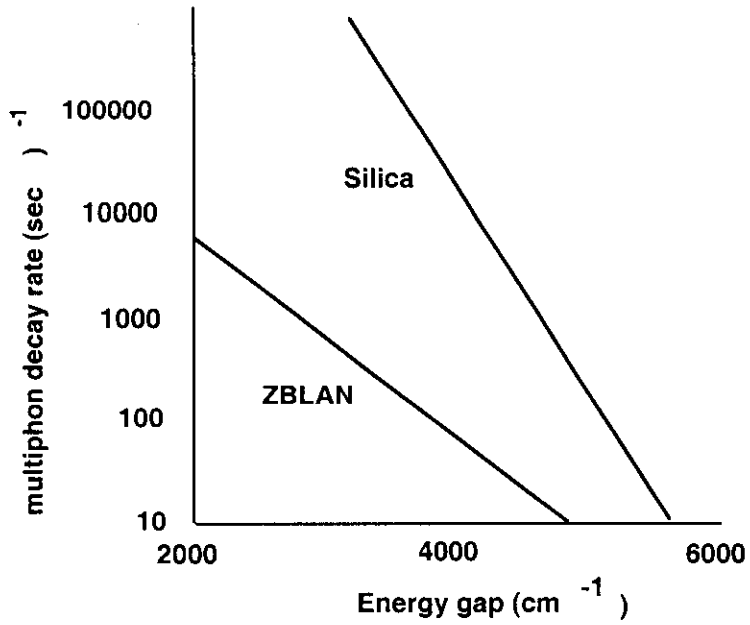


Figure 6. Phonon induced decay rate as a function of the energy gap between levels in silica and ZBLAN hosts

As a result of this, rare-earths in ZBLAN hosts exhibit many more metastable states than in silica hosts. These states will permit both lasing and the possibility of ESA or energy transfer to higher levels. This is the essential reason for the widespread use of the ZBLAN host for upconversion lasers. Having introduced the necessary background material, we will go on to discuss the main excitation and de-excitation processes in the doped fiber materials.

Excited State Absorption (ESA) and Energy Transfer (ET) processes

We will now outline the basic excitation and de-excitation processes that will determine the population dynamics of the systems of interest for upconversion: Excited State Absorption (ESA) and Energy Transfer (ET).

For ESA the basic effect is schematized on the following figure.

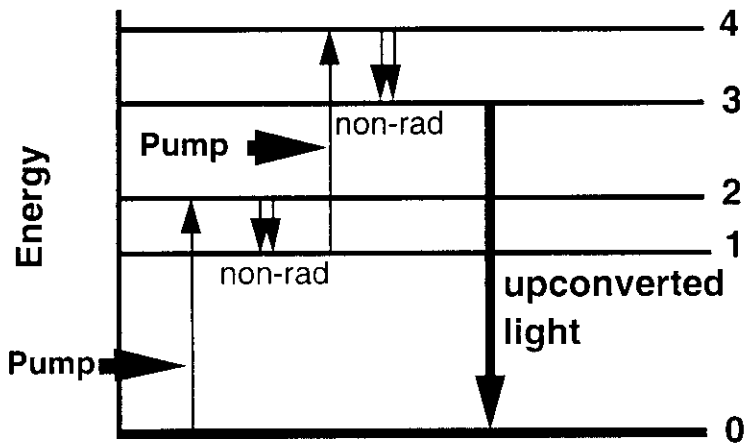


Figure 7. Schematic of a typical ESA upconversion process.

As indicated on the figure, a first pump photon is absorbed leading to an excitation of level 2 which non-radiatively decays rapidly to level 1, a metastable level. The atom in level 1 then absorbs a second pump photon to attain level 4, from which it rapidly decays non-

radiatively to level 3. Upconversion occurs when level 3 is radiatively coupled to the ground state.since, despite the energy losses due to the non-radiative processes, the 3 -1 fluorescence has a higher frequency than the pump photons. This is the simplest possible example of ESA. Clearly the process does not have to begin or terminate on the ground state, and higher order processes are possible, but figure 7 expresses the essential idea. It is also the process which leads to green fluorescence with Er doped silica fibers when pumping at 800 nm, and which we shall describe in more detail later.

Energy transfer processes can occur between identical ions, or other ions having similar energy levels, which are in close proximity to one another. In the following figure we schematize an ET process which enables an ion to non-radiatively transfer absorbed energy to a neighbouring ion.

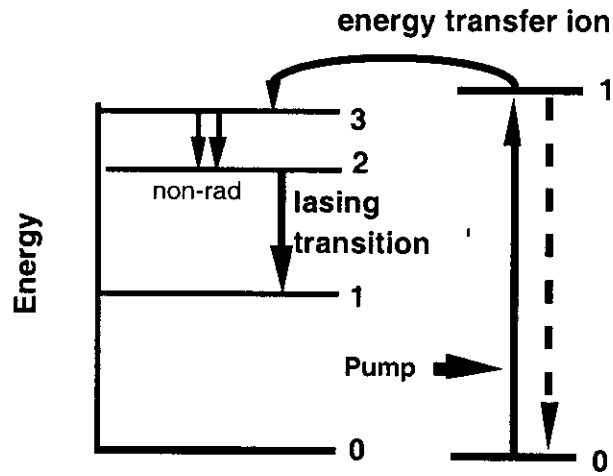


Figure 8. In this ET process an ion absorbs a pump photon and transfers the energy to a similar level in a neighbouring ion

In this processs a pump photon has been absorbed exciting the ET ion to the level 1. The ET ion then transfers it's excitation to the neighbouring ion's level 3, simultaneously relaxing to it's ground state. The lasing ion relaxes non-radiatively to the upper lasing level, 2. If there is a second excited ET ion in the vicinity of the lasing ion, and a corresponding excited state in the lasing ion having a level whose energy is around the transfer energy above the state 2, a double energy transfer (see fig. 2a) can take place leading, eventually to upconversion.

Another multiple ion phenomena which occurs is that of quenching. This process is schematized in the following figure.

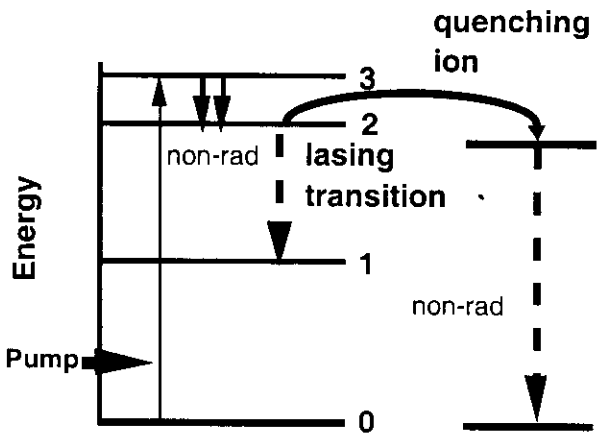


Figure 9. Quenching of an excited state due to ET to a neighbouring ion.

In this example, typical for a four-level laser ion such as Nd , the pump photon is absorbed to excite level 3 which rapidly relaxes non-radiatively to the upper lasing level, 2. In the presence of a quenching ion the excitation can be trasferred to that ion thereby reducing the population of the excited state and lowering the pumping efficiency. Such transfers do not always have deleterious effects. They can be used to advantage, for example to depopulate a relatively long lived terminal laser transition level, or, as we shall show, to realize useful technological devices such as the molecular beacon we shall describe in the application section.

Having identified and described most of the essential phenomena involved in the excitation and de-excitation of rare-earth ions we are, finally, in a position to describe some fiber upconversion lasers, which we shall do in the following section.

Examples of upconversion lasers

While upconversion lasers had been demonstrated in pulsed and CW low-temperature versions previously, the paper of Allain et al[8] on the first CW room temperature upconversion fiber laser was a major breakthrough. This laser was based on a holmium doped (1200 ppm by weight) ZBLAN monomode fiber of around 1 m length. The fiber laser was pumped by a krypton laser operating at 647 nm and had a threshold of about 150 mw. It produced up to 10 mw of power at 550 nm and exhibited a slope efficiency of approximately 20%. While this was a very impressive accomplishment, more recent work has centered on the use of thulium doped ZBLAN and has led to efficient upconversion fiber lasers operating at 480 nm and we shall describe these lasers in more detail

The first CW room temperature blue upconversion laser was reported by Grubb et al[9]. The fiber used was a 1000 ppm Tm^{3+} doped 2 m long ZBLAN fibre with a numerical aperure of 0.21 and an LP11 cut-off wavelength of 800 nm. The pump was a Nd:YAG laser operating on three closely spaced lines at 1112, 1116, and 1123 nm. The three step ESA upconversion pumping scheme used is shown on the following figure.

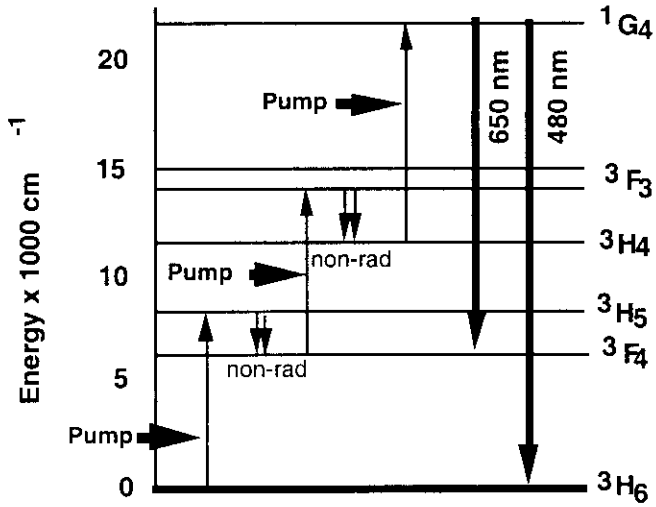


Figure 10. Three photon ESA pumping scheme for 650 and 480 nm laser action in Tm^{3+} doped ZBLAN fibers.

The first version of this laser had a threshold of 46 mw of coupled pump power and a 32% slope effiicency with respect to absorbed pump power. The maximum output was 56 mw.

More recently, output powers of up to 230 mW of power were demonstrated with a 1.6 W Nd:YAG pump[10] and 106 mw of 480 nm light has been obtained using two diode lasers as a pump for a nearly identical fiber[11]. The threshold for the latter device (an incident power threshold of 80 mw was cited) and slope efficiency were very close to those of the

configuration in reference 9. We believe this to be the most interesting frequency conversion schemes realized to date with diode laser pumping and it certainly gives a glimpse of the type of devices we might see appearing commercially in the near future.

Before leaving the discussion of such lasers it is worth noting that in view of the complexity of the rare-earth spectra and the various means of obtaining upconversion, it is still possible that other combinations of ESA and/or ET will lead to viable lasers. One extensively studied possible material is Pr doped and co-doped ZBLAN which has led to dual wavelength pumped lasers[12] based on ESA, and single wavelength pumping of Nd:Pr doped fiber[13], which could also prove to be useful. Nevertheless, since the performance of these devices is not equal to the Tm doped systems we shall not discuss them any further. They are simply cited as examples of the multiplicity of posible paths to upconversion fiber lasers in general.

Nevertheless, while these lasers allow quite acceptable nm tolerances for the pump wavelength they suffer from the extremely high current prices of the ZBLAN fibers. An order of magnitude reduction will probably be necessary to make such lasers commercially viable.

Having concluded this discussion of upconversion fiber lasers, we shall now go on to describe the state of the art of short wavelength diode lasers.

SHORT WAVELENGTH DIODE LASERS

In view of the applications for short-wavelength lasers, it might seem surprising that the first demonstration of a blue-green injection laser came nearly 30 years after the first such lasers realised in the GaAs system. While lasing had been demonstrated in the wide-gap II-VI semiconductors using optical and e-beam pumping the report of Haase et al [14]in 1991 of injection pumped lasing at 490 nm in ZnCdSe-Zn(S)Se was practically a surprise. Research workers had clearly identified the most significant problem as the inability to realize highly p-doped materials.This was overcome through the development of nitrogen doping using an RF (radio-frequency) plasma source which permitted attaining the 10^{18} cm^{-3} range of dopant concentration. This allowed operation of a gain guided laser having the structure shown in the following figure.

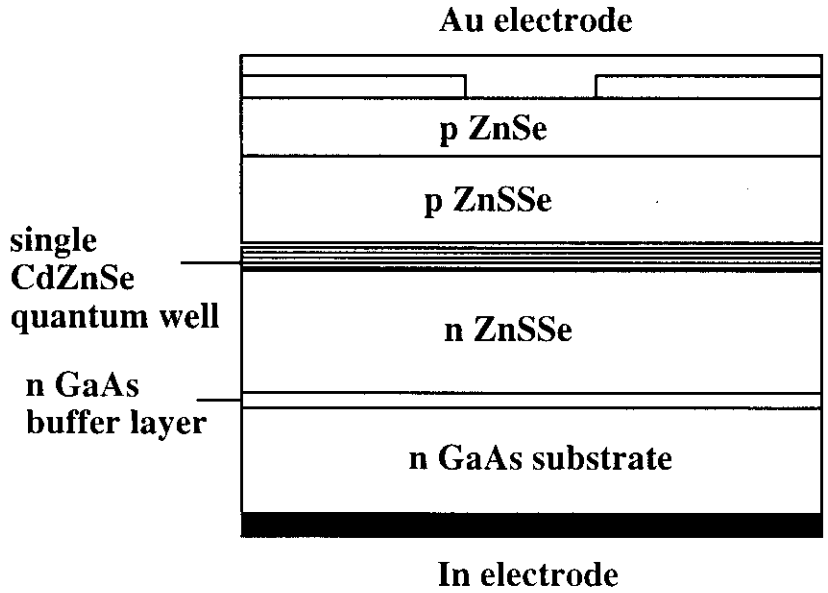


Figure11. . Highly simplified schematic of a ZnSe injection laser structure.

The laser functionned in a pulsed mode with a threshold of around 70 mA at a temperature of 77 K.

This report led to a considerable amount of research activity throughout the world, leading to a demonstration of CW operation at room temperature by a group at Sony in 1993[15]. Currently, CW operation of such lasers has attained 100 hour levels at room temperature [16]. This limitation is apparently imposed by the formation of nonradiative centers during current injection. The degradation mechanism apparently originates at pre-existing defects which are created when the first layers of ZnS nucleate on the GaAs substrate. Incorrectly aligned atoms form stacking faults which expand during subsequent crystal growth to become so-called dark-line defects which then propagate to in or near the active layer. In the active quantum well region these faults present sites for non-radiative recombination of electrons and holes which leads to a release of around 2.5 eV of energy, a level capable of creating further defects, and hence, rapid degradation. A major part of the research on this system consists of characterizing, in the hope of eventually eliminating, the defect nucleation sites.

However progress at this time seems to be more rapid using another class of mateials based on GaN and it's alloys. It was only in 1994 that the extensive research on the Al-Ga-In-N alloy family led to dramatic results- the commercialization by Nichia, a Japanese company, of extremely bright LED's emitting in the green to ultraviolet range. This was followed by the announcement by the same group of injection laser operation under pulsed conditions in late 1995 [17] and a CW room temperature version emitting 1.5 mw per facet around 420 nm and lasting 35 hours, with operating currents between 100 to 280 mA, in 1996[18]. Finally in 1999 blue diode lasers became commercially available, albeit at a price of several thousand dollars.

The type of structure used is highly schematically shown in the following figure.

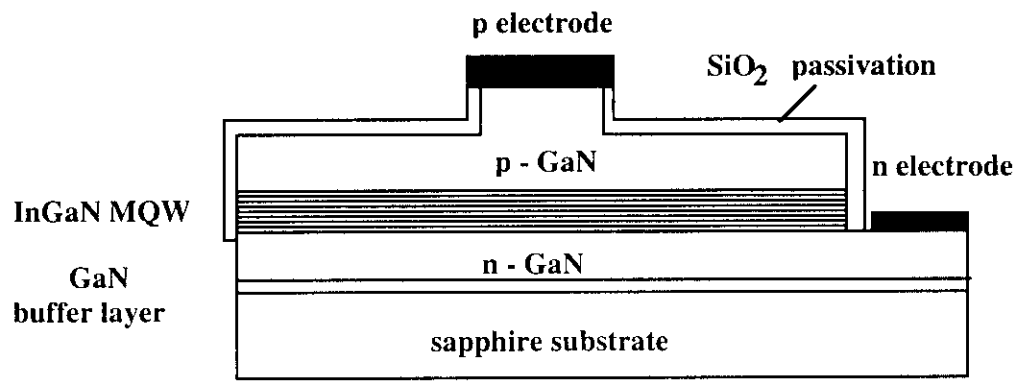


Figure 12. Highly simplified schematic of a GaN injection laser..

Obvious differences with other laser structures include the fact that the substrate is an insulating crystal. This leads to the necessity of depositing the n electrode at the side of the structure and adapting the buffer layer to the sapphire structure.

While these lasers still have threshold current densities on the order of 3 kA/cm2, an order of magnitude greater than GaAs lasers, the defect structures, which are proving difficult to eliminate in the II-VI lasers, appear to be far less deleterious in the nitrides. The technology is continuing to develop, with a strong push coming from the display applications for which GaN LED arrays are already commercially available. This combination of an existing market (display) as well as the promise of blue lasers seems to give a strong advantage to the GaN family in the ongoing race towards reliable short wavelength diode sources.

PARAMETRIC SOURCES

The parametric process that has been most developped for the practical generation of CW blue light is Second Harmonic Generation (SHG). For the power levels we are considering, on the order of 10 mW, the Quasi-Phase-Matched (QPM) waveguide configuration, realized in lithium niobate or tantalate, described in the lectures of Professors Stegeman and Fejer at this institute, appears to be the most promising. Since the underlying phenomena and theory have been developped in those courses we shall only present the briefest of outlines here before proceeding to a comparison with the other techniques. The basic QPM waveguide configuration is shown on the following figure.

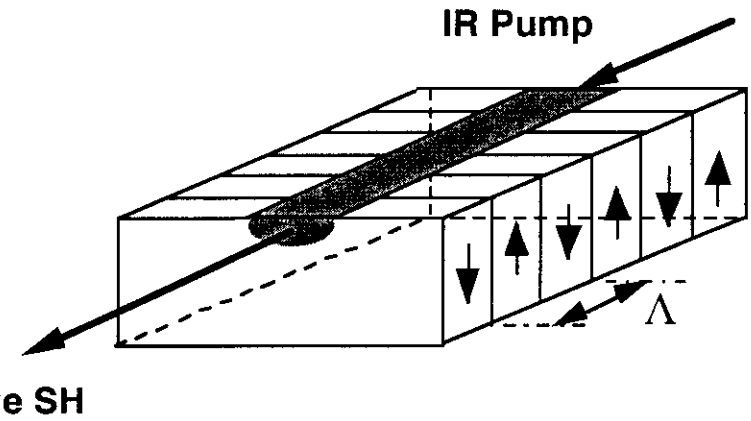


Figure 13. Basic waveguide QPM configuration for SHG.

The essential idea is that the periodically inversed domains, and hence sign-inverted nonlinear coefficients, correct the π dephasing developped between the nonlinear polarization and the propagating wave at the harmonic frequency. This clever idea, first proposed by the group of Bloembergen[19] was demonstrated in waveguide form in 1989 by groups at Stanford[20] and the Institute of Optical Resarch in Stockholm[21]. Extensive analyses of the tolerances on periodicity, waveguide regularity, pump wavelength spectrum, and temperature variations have been carried out by the two groups[22,23]. In reference 23 the authors presented a very useful formula giving the following first-order Taylor series expansion approximation of the full width at half maximum (FWHM) acceptance bandwith of the SHG efficiency for an arbitrary parameters variation: $\delta\xi = \frac{5.57}{L}\left|\frac{\partial\Delta k}{\partial\xi}\right|^{-1}$

where ξ is the arbitrary parameter and $\Delta k = k_2 - 2k_1 - K_m$ with K_m the inversion period for the m^{th} order QPM being used. For the frequency doubling of 860 nm light this indicates that the FWHM tolerances for a 1 cm long sample in lithium niobate are approximately those given in the following table.

parameter	$\delta\lambda$ (nm)	δT(°K)	$\delta\upsilon_Z$ (mrad)	$\delta\upsilon_O$(mrad)
	.07	1.4	11	10

Table 1 FWHM acceptance bandwidth for doubling of aan 850 nm source with a 1 cm long QPM lithium niobate saample. $\delta\upsilon_Z$ and $\delta\upsilon_O$ represent angular deviations of the sample cut around the z and ordinary axes respectively.

While such tolerances appear rather draconian, a recent development in the field of diode laser pumps should allow satisfying these conditions. The device in question is an electrically tunable, high power, single frequency diode laser fabricated by SDL[24]. The stucture consists of a Distributed Bragg Reflector (DBR) configuration with separate electrodes allowing independant current injection in the gain and DBR regions. Injection of current in the DBR region locally heats the grating leading to an increase of the emittted wavelength. The device can be tuned over a 10 nm range in 0.08 nm steps, the steps being due to the longitudinal mode separation in the cavity. Such devices have already demonstrated over 20, 000 hour lifetimes, in ongoing tests, while emitting 200 mW continuously.

That such a device, in conjunction with a lithium niobate QPM doubler, is a viable source for optical disk recording is underscored by the recent (June 9, 1997) announcement by Panasonic, of the realization of a complete recording head based on this technology. The source, using an X-cut MgO doped periodically poled lithium niobate crystal[25]with an overlay of Nb_2O_5 provides 15 mW of power at 425 nm without demonstrating photorefractive effects. The direct modulation permitted by the source allowed the demonstration of the reading and writing of optical discs corresponding to a 15 GB/face capacity, roughly a 4-fold improvement over existing technology.

In conclusion, in view of the performance of the system reported by Panasonic, it looks like near IR diode laser pumped QPM parametric generators could become the first example of a nonlinear optical mass consumer application. If this should come to pass, the repercussions would be enormous for the field of nonlinear optics as the market would generate the means for an enormous expansion of related research and development.

OTHER EXAMPLES OF APPLICATIONS

In this section we shall describe three examples of techniques and devices based on the various excitation and de-excitation phenomena we have presented. To underline the sort of pleasant surprises science can afford us we will begin with two examples based on what are usually considered to be nefast phenomena. The first is a fiber optic temperature sensor, the second is a molecular beacon technique used for genetic identification. We shall conclude with a description of a fluorescent waveguide examination technique.

An ESA based auto-referenced silica fiber optical temperature sensor

In this section we will describe a fiber optic temperature sensor based on ESA in Er doped silica fiber, that will illustrate some of the particularities one can encounter in rare-earth spectroscopy. The ESA in question is the green fluorescence observed when pumping erbium doped fibers with 800 nm light, and is the essential reason that such pumps cannot be

used for Er doped fiber amplifiers. The ESA phenomena is schematically shown in fig14.

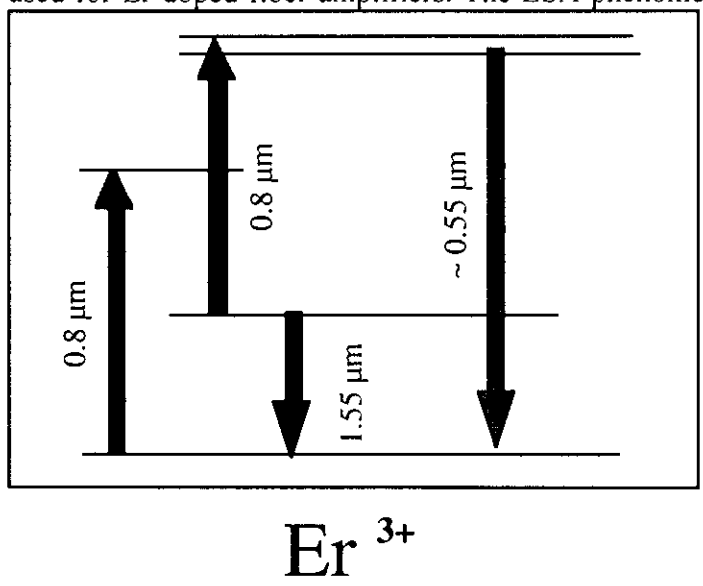


Figure 14. The 550 nm green fluorescence due to ESA of 800 nm light

A closer examination shows that the upper level of the green fluorescence is in fact two levels that are thermally quasi-isolated from the rest of the atomic system. These two levels, which thermalize rapidly between themselves, give rise to two overlapping components of green fluorescence as shown in the following figure.

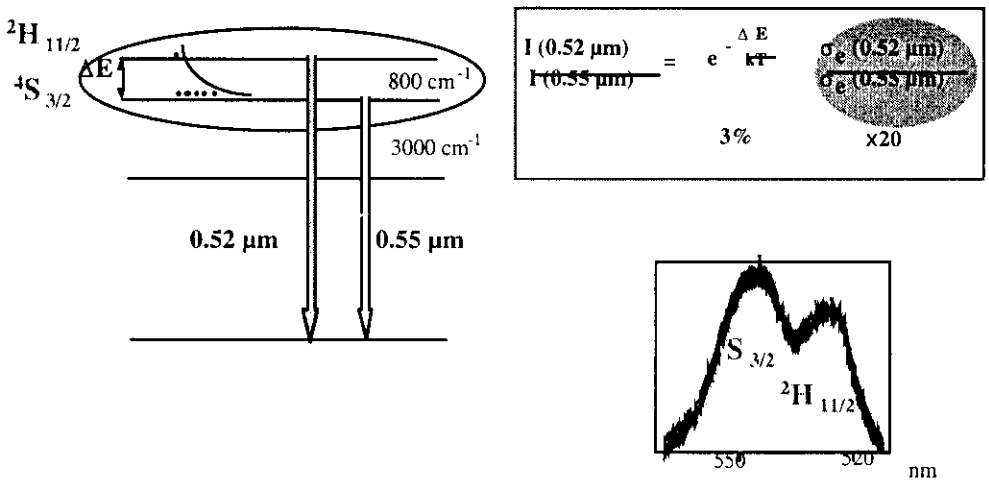


Figure 15. Two component green fluorescence due to Er ESA

A measurement of the intensity ratio of the two lines allows determining the temperature. An important point to note is that the measurement is based on an intensity ratio eliminating the need for calibration. Another important point to note, as shown in the figure inset, is that the intensity coming from the small (3%) population of the upper excited state level at ambiant temperature is compensated by its 20 times larger emission cross section, resulting in roughly equal total fluorescence for the two components. It is this gift of nature that allows the temperature sensor to have an extremely large dynamic range.A schematic of the

experiment carried out to verify this, and the experimental results, are shown in the following figures.

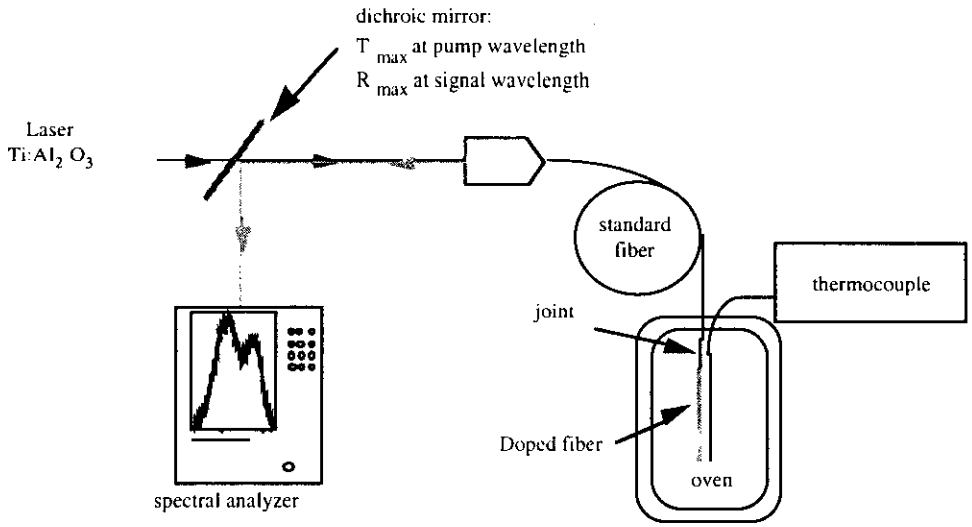
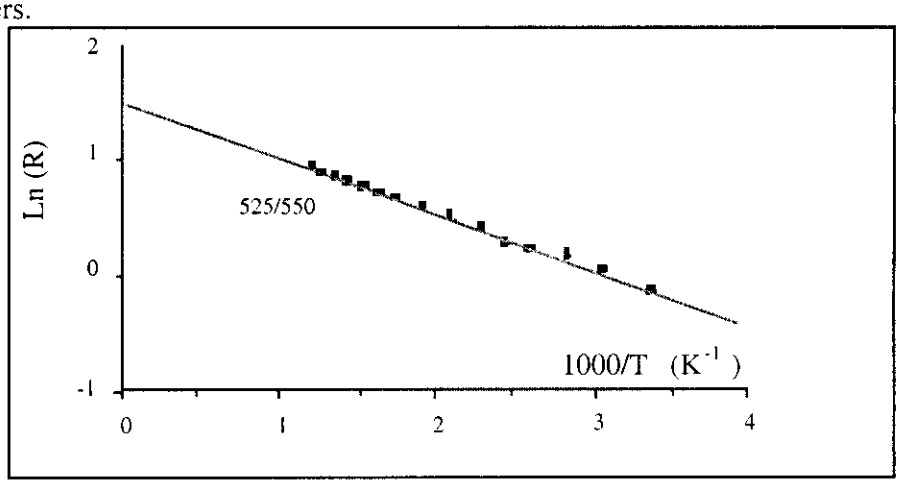


Figure 16. Experimental schematic of the ESA based temperature sensor.

In this set-up the doped fiber, typically 50cm long, was spliced to a 20 meter length of standard telecommunication fiber. Power levels in the 50 to 200 mW range, at 850 nm were supplied by the Ti:saphire laser, which could be replaced by commercially available diode lasers.



Dynamic : 12 dB (0 - 600°C)
Sensibility : 0.5 °C
auto-referenced sensor

Figure 17. Experimental results for the ESA based fiber temperature sensor.

This sensor can also be excited by an energy transfer process using Yb-Er codoped fibers and a 980 nm pump and quasi-distributed, rather than point sensors, can be realized by analyzing the ratio of 1130 and 1240 nm lines which also appear when pumping at 800 nm[26], but a discussion of this configuration would take us too far afield from the subject of upconversion.

Molecular beacons

The molecular beacon is another application of blue light that is based on an apparently nefast phenomenon: fluorescence quenching by a neighbouring ion. This phenomenon is one in which an excited atom, capable of fluorescing, transfers it's energy non-radiatively, to another ion, which then decays, also nonradiatively, to it's ground state. This sort of quenching is common in the rare-earths and is the sort of process that limits the useful doping levels to a few per cent. However, such a phenomenon has been put to good use in a "device" for genetic identification: the molecular beacon[27]. The structure of such a beacon is shown in the following figure.

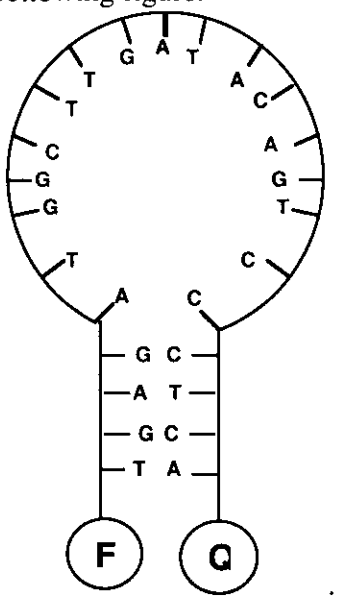


Figure 18. A molecular beacon consisting of a single strand of DNA folded back upon itself with a fluorescent (F) and quencher (Q) molecule attached at the extremity.

The letters A,C,G, and T represent the adenine, cytosine, guanine,and thymine molecules attached to the DNA strand. Adenine links to thymine and guanine to cytosine to form the famous double helix. In the beacon extremity the complementary molecules are used to close the structure and fluorescent and quencher molecules are attached to opposite sides of the strand. Commonly used molecules are fluorescin for the fluorophore and DABCYL for the quenching molecule. As long as the extremity of the structure is closed, the proximity of the quenching molecule will inhibit fluorescence when the beacon is illuminated with blue light. When such a structure is placed in a solution containing single strands of DNA it will move about due to thermal fluctuations, and attach itself to the normal, much longer DNA strands if it finds a complementarily coded segment. Since the longer segment is much more rigid, attachment will force the closed end of the beacon open, separating the F and Q molecules, allowing fluorescence, and hence localisation of the researched segment. Such beacons allow the discrimination between segments that differ from one another by only a single nucleotide[28]. This technique is expected to play a major role in future research on gene sequence identification and manipulation.

Having concluded our two example of good uses of usually nefast phenomena, we will go on to describe our last example of blue light or upconversion processes, waveguide examination by fluorescence.

Waveguide examination by fluorescence

While calculations give beautiful graphics concerning the evolution of fields in integrated optical devices it is rather difficult to directly observe such fields. What one usually observes when looking at a waveguide are scattering centers which do not yield a reliable image of the fields. A technique that has been demonstrated for overcoming this is to coat the guide with a

low index plastic film doped with a fluorescent material and observe the emitted fluorescence induced by the evanescent wave. This fluorescence, which is directly proportional to the local guided wave power, gives an excellent map of the field[29]. A schematic of the experimental setup is shown on the following figure.

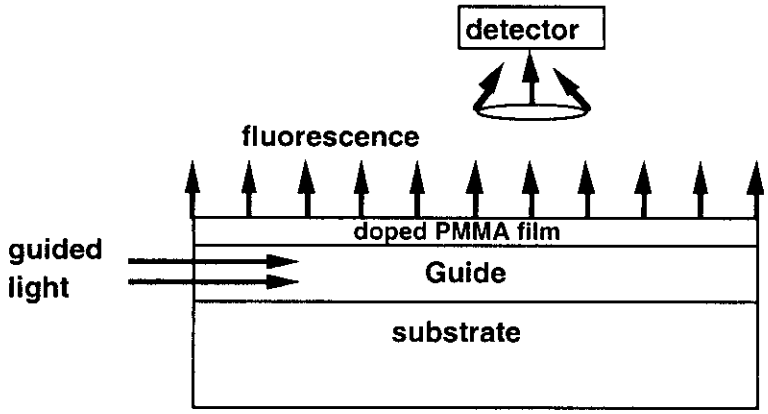


Figure 19. Schematic of the waveguide observation by fluorescence set-up.

In the first experiments demonstrating this effect the guide was realized using polyphenylsiloxane (PPS), an electron resist material that allowed direct e-beam writing of guides[30].In these experiments a structure consisted of an 800 nm thick PPS guide with an index of 1.565 at 632 nm, covered with a 300 nm polymethylmethacrylate (PMMA) film with an index of 1.49, doped with 6% by weight of Rhodamine B. This molecule exhibits an interesting anti-Stokes fluorescence line (an upconversion process we have not discussed) at 595 nm when pumped with a He-Ne laser. In the structure described approximately 10% of the guided light propagates in the evanescent field within the doped film and 3 mW of guided light leads to a fluorescence power on the order of 10^{-10} W/μm^2 emitted from the guide surface which is a detectable power level. This allowed, therefore, field maps to be made in varying structures such as couplers, Y-junctions and curved guides. In order to observe the fields propagating in lithium niobate and tantalate guides, which, due to their higher indices, only have on the order of 1% of the guided light in the evanescent field, it was necessary to dope with Rhodamine 6G and pump with a blue line of an argon laser. This yielded equivalent fluorescent power and allowed the observation of fields propagating in these materials. A chosen few have even seen a film made with this technique that demonstrates the observation of switching in electrically controlled lithium niobate directional couplers[31].

Since this direct observation of switching is as close to the main thrust area of this institiute as we shall get in this contribution, we choose to draw the curtain here.

CONCLUSION

In this course we have described the current state of the art concerning three technologies being used to realize low-power coherent short wavelength sources: upconversion fiber lasers, diode lasers, and second harmonic generation. We have also gone at some length into describing three rather original applications for such sources and their technology: a fiber optic temperature sensor based on upconversion, a DNA recognition technique, and a waveguide examination technique, both of the latter using short wavelength induced fluoresence. We hope to have shown that this is a rapidly evolving field, involving pluridisciplinary interactions, that has led to important results, and will, in the future continue to provide, as it has in the past, pleasant surprises.

While this terminates the technical part of this paper, I would like to take advantage of this opportunity to present my opinions concerning a topic discussed during the round table of the school: what we mean when we speak of "applications". While it would be foolhardy for any scientist to claim that certain phenomena will never serve any "useful" purpose, it appears to me that over the pasr few years we have tended to go overboard in the other direction. By this I mean that researchers sometimes apparently feel a need to justify their work by dangling the image of impending "products" throughout their discourse. The applications we have heard of concerning both spatial solitons and cascaded switches are cases in point. Even if the applications suggested are not totally impossible, the implications can be construed , at this point, as misleading. The scientific work presented is capable of standing on it's own without such a crutch. While the eventual applications one can imagine might be tantalizing one must walk a fine line to avoid "selling the skin of the bear before you kill it".

The author wishes to acknowledge fruitful discussions with P. Gibart concerning GaN and ZnS lasers, Jean-Pierre Lehureau, concerning compact disc technology, Albert Libchaber and Gregoire Bonnet, concerning molecular beacons, Jean-Paul Pocholle, Gerard Monnom and Bernard Dussardier concerning rare-earth doped fibers, and Arnaud Grisard, Marc De Micheli and Pascal Baldi concerning parametric sources. Thanks also to professor N. Bloembergen for offering me the "skin of the bear" quotation upon learning that I was having my Ph. D. celebration party the week before the defense.

Finally, the author alone is totally responsable for any errors introduced as well as the opinions offered.

REFERENCES

1. E. Snitzer, Optical maser action of Nd^{3+} in barium crown glass, *Phys. Rev. Letts.* 7: 444, (1961)
2. J.R. Armitrage, Introduction of glass fiber lasers and amplifiers, in:*Optical Fiber Lasers and Amplifiers*, ed P.W. France, CRC Press (1991)
3. N. Bloembergen, Upconversion quantum counter, *Phys. Rev. Letts.* 2: 84 (1959)
4. T. Kushida and M. Tamatani, Conversion of infrared into visible light, supplement to *J. Japan Soc. Appl. Phys.* 3: 241 (1970), F. Auzel, Materials and devices using double-pumped phosphors with energy transfer, *Proc. I.E.E.E.* 61: 758 (1973)
5. F. Auzel, Compteur quantique par transfert d'énergie enttre deux ions de terres rares dans u
6. M. Poulain, M. Poulain, and J. Lucas, Fluorozirconate glass, *Mat. Res. Bull.* 10: 243 (1975)
7. Zheng H. and Gan F. Fluorozirconate glass phonon spectra, *Chinese Phys.* 6: 978 (1986)
8. J.Y. Allain, M. Monerie, and H. Poignant, Room temperature CW tunable green upconversion holmium fibre laser, *Electron. Lett.* 26: 261 (1990)
9. S.G. Grubb, K.W. Bennett, R.S. Cannon and W.F. Humer, CW room-temperature blue upconversion fibre laser, *Electron. Lett.* 28: 1243 (1992)
10. R. Paschetta, N. Moore, W.A. Clarkson, A.C. Tropper, D.C. Hanna, G. Mazé, 230 mWof blue light from thulium:ZBLAN upconversion fiber laser, *Proceedings CEO 97 paper CTuG3* : 80 (1997).
11. S. Sanders, R.G. Waarts, D.G. Mehuys, and F.D. Welch, Laser diode pumped 106 mW blue upconversion laser, *Appl. Phys. Lett.* 67 : 1815, (1995).
12. R.G. Smart, D.C. Hanna, A.C. Tropper, S.T. Davey, S.F. Carter, and D. Szebesta,

Upconversion fiber laser, *Electron. Lett.* 2:, 1307 (1991).
[13]. S.C. Goh, R. Pattie, C. Byrne, and D. Coulson, Blue and red laser action in Nd3+: Pr3+ co-doped fluorozirconate glass, *Appl. Phys. Lett.*, 67: 768 (1995).
[14]. M.A. Haase, J. Qui, J.M. Depuyt, and H. Cheng, Blue-green diode laser, *Appl. Phys. Lett.* 59: 272, (1991)
[15]. N. Nakayama, et al, CW operation of a ZnSe laser at room temperature, *Electron. Lett.* 20:. 2194 (1993)
[16]. S. Tanaguchi, etal, 100 hour operation of a ZnSe diode laser, *Electron. Lett.*, 552, (1996)
[17]. Nakamura, S., et al , InGaN multi-quantum-well structure laser diodes, *Jpn. J. Appl. Phys.* 35: L74 (1996)
[18]. Nakamura, S. Characteristics of InGaN multi-quantum-well structure laser diodes, *Mater. Res. Sec. Soc.* 449 :1135 (1996)
[19]. J.A. Arrmstrong, N. Bloembergen, J. Ducuing, and P.S. Pershan, Interactins between light waves in a nonlinear dielectric, *Phys. Rev.* 127: 1918 (1962)
[20]. E.J. Lim, M.M. Fejer, R.L. Byer, and W.J. Koslovsky, Blue light generation by frequency doubling in a periodically poled lithium niobate channel waveguide, *Electron. Lett.*25: 731 (1989).
[21]. J. Webjorn, F. Laurell, and G. Arvidsson, Blue light generated by frequency doubling of laser diode light in a lithium niobate channel waveguide, *IEEE Photon. Technol. Lett* 1: 316 (1989)
[22]. S. Helmfrid and G. Arvidsson, Influence of randomly varying domain lengths and nonuniform effective index on second-harmonic-generation in quasi-phase-matched waveguides, *J. Opt. Soc. Am. B.* 8,: 797 (1991)
[23]. M.M. Fejer, G.A. Magel, D.H. Jundt, and R.L. Byer, Quasi-phase-matched second harmonic generation tuning and tolerances, *IEEE J. Quantum Electron.* 28: 2631 (1992)
[24]. V.N. Gulgazov, H. Zhao, D. Nam, J.S. Major, and T. Koch, Tunable high-power AlGaAs distributed Bragg reflector laser diodes, *Electron. Lett.* 33: 58 (1997)
[25]. K. Mizuuchi, K. Yamamoto and M. Kato, Harmonic blue light generation in X-cut Mg0:LiNbO3 waveguide, *Electron. Lett.* 33: 80 (1997)
[26]. E. Maurice, G. Monnom, D.B. Ostrowsky, and G.W. Baxter, 1.2-μm transitions in erbium-doped fibers: the possibility of quasi-distributed temperature sensors, *Appl. Optics*, 34: 4196,(1995)
[27]. S. Tyagi and F;R; Kramer, A molecular beacon for gene identification, *Nature Biotechnol*, 14: 303 (1996)
[28]. G. Bonnet, S. Tyagi, F.R. Kramer, and A. Libchaber, Molecular beacons for probing information in DNA, to be published
[29]. D.B. Ostrowsky and A.M. Roy, Visualisation de la propagation dans un guide d'onde optique par fluorescence anti-Stokes, *Revue tech. Thomson-CSF*, 6: 973 (1974)
[30]. D.B. Ostrowsky, M. Papuchon, A.M. Roy, et J. Trotel, Electron beam fabrication using an electron sensible film, *App. Opt.* 13: 636 (1974).
[31]. M. Papuchon, B. Puech, C. Puech, and D.B. Ostrowsky, A movie on the visualization by fluorescence of the electrically controlled directional coupler, *Proceedings of the Topical Meeting on Integrated and Guided Wave Optics.* Paper Tu A2, Salt Lake City, (1978)