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# Polychromatic Laser Guide Star using a single laser at 330 nm

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## ABSTRACT

The differential atmospheric tip-tilt can be measured using a Polychromatic Laser Guide Star. A two photon excitation has been proposed. It consists in exciting the  $4D_{5/2}$  level of mesospheric sodium atoms with two identical lasers operating at 589 nm and 569 nm. With two modeless lasers of  $2 \times 15W$  at the mesosphere level, this scheme will produce a returned flux at 330 nm of about  $4 \times 10^4$  photons/s/m<sup>2</sup>. Thanks to our modeless laser, we propose a new method which consists in exciting directly the  $4P_{3/2}$  sodium level with one photon excitation, using a single laser operating at 330 nm. This solution was previously rejected probably because of strong saturation problems using single longitudinal mode lasers. We show that 1 W modeless laser at 330 nm can produce the same returned flux at 330 nm. This solution will save at least 400 k€ of equipment. Moreover, our new method is very promising in terms of simplicity but also in terms of flux because the returned flux above will probably be not sufficient for getting a good Strehl ratio. We propose very efficient solid state laser systems for the production of tens of watts at 330 nm.

**Keywords:** Laser guide star, polychromatic laser guide star, sodium, laser-sodium interaction, atomic model, UV excitation, modeless laser, atmospheric tip-tilt, adaptive optics, solid state laser, UV laser.

## 1. INTRODUCTION

### 1.1 Monochromatic Laser Guide Star

To increase the sky coverage using adaptive optics (AO), large astronomical facilities implement monochromatic laser guide star (LGS)<sup>1,2,3,4,5</sup>. Three telescopes of 8-10 meters are now equipped with LGS. An important progress was achieved in 2004 on a 10 meter family telescope at Keck Observatory<sup>6</sup> where AO works well thanks to a natural guide star for tip-tilt correction (TTNGS from « tip-tilt natural guide star ») and a 9.5<sup>th</sup> magnitude LGS for higher order corrections. Under normal seeing conditions, the Keck LGS AO system produces K-band Strehl ratios between 30 and 40% using bright tip-tilt guide stars of 14<sup>th</sup> magnitude. The Keck II LGS AO is becoming a prolific system from an astronomical point of view. Thirty LGS AO science nights have been allocated in the second half of 2005. The Keck II laser is a 12 watt<sup>7</sup> dye MOPA laser channel fabricated by Lawrence Livermore National Laboratory (LLNL) and delivered in 1998<sup>8</sup>. The laser beam is launched on the side of the primary mirror which gives asymmetric elongation spots on the wave front sensor. The Gemini North Laser Guide Star Program was launched back in early 1999 with the beginning of an active search for a suitable laser solid state laser developed by Coherent Technologies Inc. The 12 Watts Gemini North laser is a frequency mixing of two mode locked YAG lasers at 1.319  $\mu$ m and 1.064  $\mu$ m with 750 ps pulse-width and mode-locked frequency of 76 MHz. The laser is directly fixed on the telescope structure. The laser beam is launched behind the secondary mirror which gives smaller symmetric elongation spots on the wave front sensor. Gemini North got its first LGS light in 2005<sup>9</sup>. ESO has also developed an 8W cw dye laser (PARSEC) which is also launched behind the secondary mirror of VLT. The beam is propagated to the projector using a PCF optical fibre. ESO got very recently its first light<sup>10</sup>. These three LGS systems give approximately the same returned flux at 589 nm ( $\sim 10^6$  photons/s/m<sup>2</sup>) and same LGS size (1-1.4 arcsec).

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## 1.2 Polychromatic Laser Guide Star

However, the apparent direction of the LGS is independent of the tip-tilt. Therefore the tip-tilt cannot be measured. The way to overcome the tip-tilt indetermination problem of LGSs is to use a natural guide star (TTNGS). As a result, another limitation came out: the probability to find a natural star bright enough is very small in the case of visible observation<sup>11</sup>. The way to increase the sky coverage up to 100% is to use a polychromatic laser guide star (PLGS)<sup>12</sup>. The concept of the PLGS relies on the chromatic properties of the atmospheric refractive index. It consists in exciting mesospheric sodium atoms up to a level from which a radiative decay produces chromatic components spanning from a large enough spectral range. The 330 nm transition from the  $4P_{3/2}$  level to the ground state  $3S_{1/2}$  is of special interest due to the large dispersion of the atmosphere at this wavelength. The tip-tilt angle  $\theta$  can then be corrected through the measurement of the differential tip-tilt  $\Delta\theta$  between two chromatic components (TTLGS for “tip-tilt laser guide star”). The relation between  $\theta$  and  $\Delta\theta$  is:  $\theta = (n_3 - 1) / \Delta n \cdot \Delta\theta \approx 20 \cdot \Delta\theta$  where  $n_3$  is the refractive index at the observation wavelength and  $\Delta n$  is the differential refractive index of the two chromatic components. Depending on the chromatic components the refractive index factor is about 20. This means that the differential tip-tilt measurement must be 20 times more precise than the direct tip-tilt measurement with a natural guide star. The TTLGS must be extremely intense. This makes the difficulty of the PLGS concept which must be demonstrated on sky (ELPOA program). We propose a new way of sodium atoms excitation in order to increase by at least one order of magnitude the TTLGS intensity.

## 2. TIME, SPATIAL AND SPECTRAL LASERS SODIUM INTERACTION RATE EQUATION MODEL

### 2.1 Model

Figure 1b below shows the two photon excitation scheme which has been proposed 10 years ago to produce PLGSs. A double resonant excitation with two lasers at 589 nm and 569 nm puts population to the  $4D_{5/2}$  level of the sodium atom. This induces a radiative cascade from UV to IR. The  $D_2$  line can be used for the LGS and others chromatic components for the TTLGS. We have proposed<sup>13</sup> another scheme with only one laser excitation at 330 nm which is more efficient. This possibility was rejected in paper 12 probably because of strong saturation problems. Thanks to our modelless laser development<sup>14</sup> this solution becomes extremely interesting. Figure 1a below shows that the  $4P_{3/2}$  level can be directly excited, from the ground state  $3S_{1/2}$ , with a laser centered at  $30272.51\text{cm}^{-1}$  (~330nm). The goal of the model was to find the laser power one need to equal the returned flux of the sodium transition at 330 nm. We have shown that, at the mesosphere level, a laser of 1W at 330 nm is enough to get the same returned flux at 330 nm as the one which is obtained with two lasers of 15 W each at 589 nm and 569 nm.

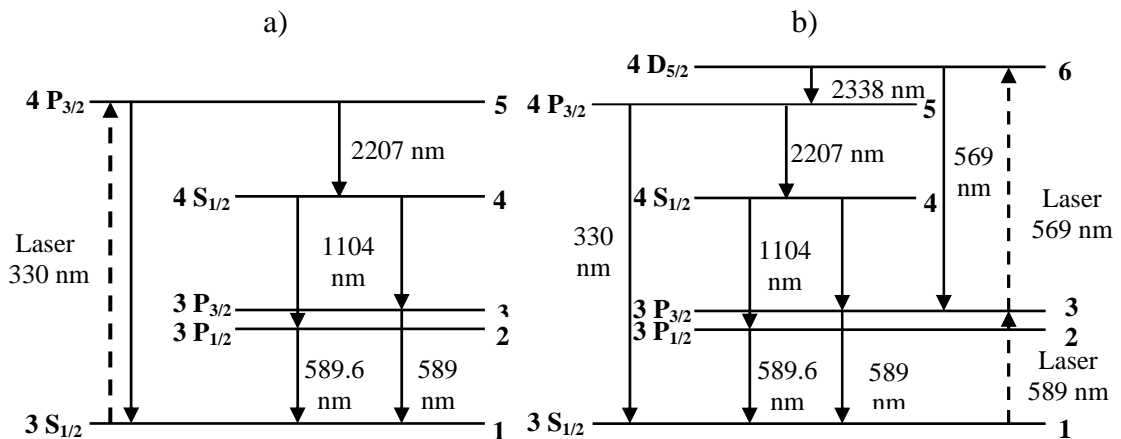


Fig. 1. Energy diagram and relaxation pathways of: a) one photon excitation of the  $4P_{3/2}$  sodium level at 330nm; b) two photon excitation of the  $4D_{5/2}$  sodium level at 589nm+569nm.

The time, spectral and spatial rate equation system that we have used is the following:

$$\begin{aligned} \frac{\partial N_1(t, \mathbf{r}, \nu)}{dt} = & -N_1(t, \mathbf{r}, \nu) \frac{g_1}{g_5} \int_{-\infty}^{+\infty} \sigma(\nu' - \nu) \Phi(t, \mathbf{r}, \nu') d\nu' \\ & + \left( \frac{N_5(t, r, \nu)}{\tau_{51}} + \frac{N_2(t, r, \nu)}{\tau_{21}} + \frac{N_3(t, r, \nu)}{\tau_{31}} \right) \\ & + N_5(t, r, \nu) \int_{-\infty}^{+\infty} \sigma(\nu' - \nu) \Phi(t, r, \nu') d\nu' \end{aligned} \quad (1)$$

$$\frac{\partial N_2(t, r, \nu)}{dt} = \frac{N_4(t, r, \nu)}{\tau_{42}} - \frac{N_2(t, r, \nu)}{\tau_{21}} \quad (2)$$

$$\frac{\partial N_3(t, r, \nu)}{dt} = \frac{N_4(r, t, \nu)}{\tau_{43}} - \frac{N_3(t, r, \nu)}{\tau_{31}} \quad (3)$$

$$\frac{\partial N_4(t, r, \nu)}{dt} = -\frac{N_4(t, r, \nu)}{\tau_{43}} - \frac{N_4(t, r, \nu)}{\tau_{42}} - \frac{N_5(t, r, \nu)}{\tau_{54}} \quad (4)$$

$$\begin{aligned} \frac{\partial N_5(t, r, \nu)}{dt} = & N_1(t, r, \nu) \int_{-\infty}^{+\infty} \sigma(\nu' - \nu) \Phi(t, r, \nu') d\nu' \\ & - \frac{N_5(t, r, \nu)}{\tau_{54}} - \frac{N_5(t, r, \nu)}{\tau_{51}} \\ & - N_5(t, r, \nu) \frac{g_1}{g_5} \int_{-\infty}^{+\infty} \sigma(\nu' - \nu) \Phi(t, r, \nu') d\nu' \end{aligned} \quad (5)$$

$$\sum_{i=1}^5 N_i(t, r, \nu) = N_D(\nu) = N_1(t=0, r, \nu) \quad (6)$$

where  $t$  is the time,  $r$  the radial position,  $\nu$  the frequency,  $g_1/g_5$  the degeneracy of the  $3S_{1/2}$  and  $4P_{3/2}$  states,  $1/\tau_{ij}$  the rate of the transition  $i \rightarrow j$ ,  $\Phi$  the laser photon flux density,  $\sigma$  the homogeneous absorption cross section,  $N_i$  the population of the level  $i$  and  $N_D$  the Doppler distribution population. Similar equations system was used for the 2 photon excitation scheme. Figure 2 summarize our calculation using lasers of 17 kHz repetition rate and 50 ns pulse width. It is clear that modeless lasers give the best result. The actual ELPOA program with the two photon excitation scheme will produce  $4 \times 10^4$  photons/s/m<sup>2</sup> as the one photon scheme with 10 W at 330 nm can produce  $3 \times 10^5$  photons/s/m<sup>2</sup>. Figure 2 shows that using single mode lasers the 330 nm excitation scheme is not relevant. Only modeless laser makes this solution very attractive. The slope of curve 3 can be larger for higher repetition rate and pulse width. A returned flux up to  $10^6$  photons/s/m<sup>2</sup> is technically attainable using robust solid state laser material with moderated mean power. This point is developed latter on.

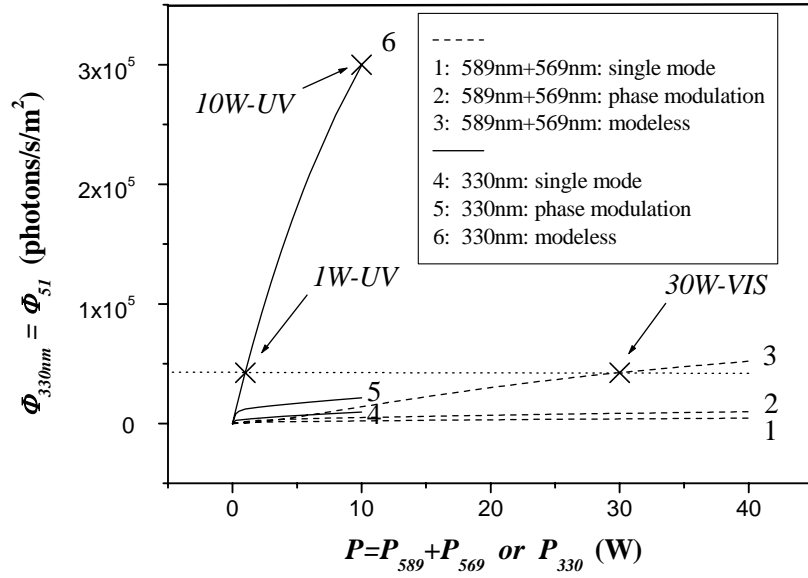


Fig. 2. Return fluorescence flux at 330nm versus average laser power for the three types of lasers: a) 1 MHz single mode laser (curves 1 and 4), b) 1 MHz single mode laser followed by a double phase modulation at 180MHz and 325 MHz (curves 2 and 5) and c) modeless laser (curves 3 and 6). Solid curves correspond to the one photon excitation at 330nm (case 1) and dashed curves to the two photon excitation at 589nm + 569nm (case 2). The cross located at 30W-VIS on curve 3 corresponds to the ELP-OA project. The cross at 1W-UV on curve 6 corresponds to the UV laser power at 330nm that equalize the flux of photons of the ELP-OA project. The cross at 10W-UV on curve 6 corresponds to the flux that is close to the required flux. 10W in case 1 gives 12 times more flux than 30W in case 2.

## 2.2 Discussion

The main three results of this work are:

1. using modeless lasers of  $2 \times 15 \text{ W}^\dagger$  at 589 nm + 569 nm or 1 W laser at 330 nm will produce the same returned flux at 330 nm ( $\sim 4 \times 10^4$  photons/s/m<sup>2</sup>).
2. for the two photon excitation scheme, the flux at 330 nm is about 100 times weaker than the flux at 589 nm (D<sub>2</sub> line).
3. if one needs 10 times more flux, only 10 W of a laser operating at 330 nm will be sufficient; whereas even with two 200 W lasers at 589 nm + 569 nm it will be extremely difficult to reach this gain (see slopes of curve 3 and 6 of figure 2).

Points 1 and 2 are in very good agreement with two theoretical works using density matrix methods. It has been demonstrated<sup>15</sup> that taking, in the two photon excitation scheme,  $2 \times 25 \text{ W}$  lasers which are able to cover all velocity classes of sodium atoms (equivalent to our modeless laser) and taking an atomic column density of  $5 \times 10^9$  atoms/cm<sup>2</sup>, a returned flux of  $10^5$  photons/s/m<sup>2</sup> is obtained. If one correct for the values of our parameters (i.e.  $2 \times 15 \text{ W}$  and  $4 \times 10^9$  atoms/cm<sup>2</sup>) one get a result which is very close to our calculation (point 1). Again in the two photon excitation scheme, it has been clearly shown<sup>16</sup> that the flux at 330 nm is 100 times weaker than the returned flux on the D<sub>2</sub> line (see figure 3 of reference 16). The consequence is that, because the measured D<sub>2</sub> flux at Keck II, Gemini and VLT/ESO is about  $10^6$  photons/s/m<sup>2</sup> with similar laser power, the two photons excitation scheme cannot produce a flux at 330 nm larger than about  $10^4$  photons/s/m<sup>2</sup>. As this flux could be largely insufficient for PLGS programs, point 3 is a very good news.

We have shown that our model is also in very good agreement with experiments on sky: PASS-1 with LLNL lasers<sup>17</sup>, PASS-2 with CEA lasers<sup>18</sup> and PASS-2 with LSP lasers.

<sup>†</sup> Laser power is given at the mesosphere level.

### 3. ONE PHOTON EXCITATION VERSUS TWO PHOTON EXCITATION

Here is summarized the advantages and disadvantages of both solutions

#### 3.1 Disadvantages of the two photon excitation

- Complex double high power modeless lasers system (see figure 3a below)
- Two identical lasers
- Time synchronization of pulses (time jitter)
- Spatial overlap of two beams
- 1 GHz line width at 569 nm difficult
- Returned flux at 330 nm limited: no real possibility to increase the flux with reasonable laser power
- No solid state laser solution

#### 3.2 Advantages of the one photon excitation

- Simple one modeless laser system (see figure 3b below)
- No time synchronization and spatial overlap
- 3.5 GHz line width at 330 nm easy (i.e. 5 GHz at 660 nm)
- ~50% population of the  $4P_{3/2}$  level by incoherent excitation
- Possibility to increase the returned flux at 330 nm up to  $10^6$  photons/s/m<sup>2</sup> with reasonable laser power
- In the later case a single 330 nm laser is enough to produce at the same time the TTLGS and LGS
- Several robust solid state laser solutions

## 4. LASERS TECHNOLOGIES

### 4.1 Dye lasers

Unfortunately no solid state lasers can generate 569 nm. For the moment only dye lasers allow these wavelengths with high powers and high efficiency. The isotopic separation programs have demonstrated that it is possible to obtain 1000 W in the visible range<sup>19</sup>. In order to solve the limitation due to the saturation of sodium transitions, we have developed a dye modeless laser. A great advantage of dye lasers is their large wavelength tunability. The same modeless laser channel can generate 589 nm, 569 nm and 330 nm. Figure 3a below shows the ELPOA laser channels under development. Because of the large hyperfine structure (1.77 GHz) of the ground state of sodium atom, the 589nm laser requires a line width of 3 GHz. It is attainable with a single intra cavity etalon (F). 15-20W can be obtained using two 50 W YAG pump lasers operating at 532 nm or CuHBr lasers<sup>20</sup>. The 569 nm channel is more difficult because the line width must be 1 GHz. This modeless laser line width has not yet been demonstrated. A more efficient intracavity etalon has to be developed which implies more intra cavity losses. Then, they must be compensated with higher cw pump power and more efficient intra cavity acousto-optic frequency shifter. According to our model and its validation on several sky experiments these two laser channels would produce a 330 nm returned flux of about  $4 \times 10^4$  photons/s/m<sup>2</sup> at the mesosphere. The same flux can be obtained using the much simpler 330 nm laser channel describes on figure 3b. Because of the lower wavelength, the required line width at 330 nm is 3.5 GHz. According to non linear effect of the second harmonic generator (SHG), the required 660 nm modeless line width is of 5 GHz. It is easily obtained without cw operation. The dye jet of the modeless oscillator can be directly pumped by 200 ns pulse width YAG laser of 3 W of mean power. Moreover, the 330nm laser channel amplifier requires only one 50 W pump YAG laser instead of four. The reliability will be much higher and for the same returned flux this solution saves at least 400 k€ of equipment.

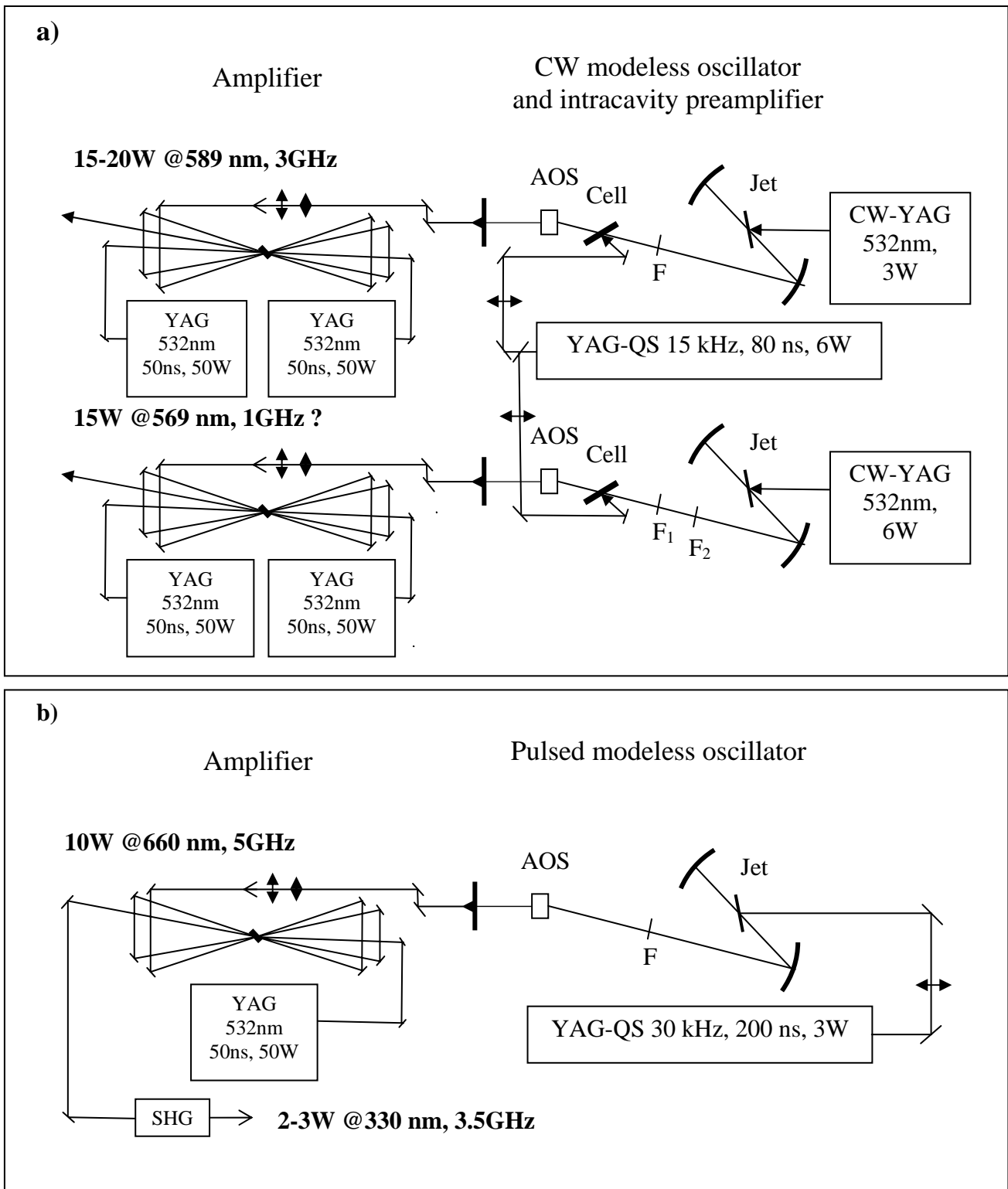


Fig 3. Two dye laser solutions for the same returned flux at 330 nm; a) for the 2 photon excitation :  $2 \times (15-20\text{W}) @589 \text{ nm} + 569 \text{ nm}$ , 3 GHz and 1 GHz dye modeless laser channels; b) for the one photon excitation:  $2-3\text{W} @330 \text{ nm}$ , 3.5 GHz dye modeless laser channel.

#### 4.2 Solid state Nd:YLF/YAG laser at 330 nm

Interesting coincidences exist for the production of the 330.3 nm line. Nd doped YAG or YLF matrix have intense laser line at 1.3  $\mu\text{m}$ . Nd:YAG and Nd:YLF give a maximum gain at respectively 1319 nm and 1321 nm. Using frequency quadrupling, a laser line at 330.3 nm can be obtained<sup>21</sup>. Figure 4 below shows the gain profile for Nd:YAG and Nd:YLF. The later is probably more favorable in terms of gain but YAG is a stronger matrix.

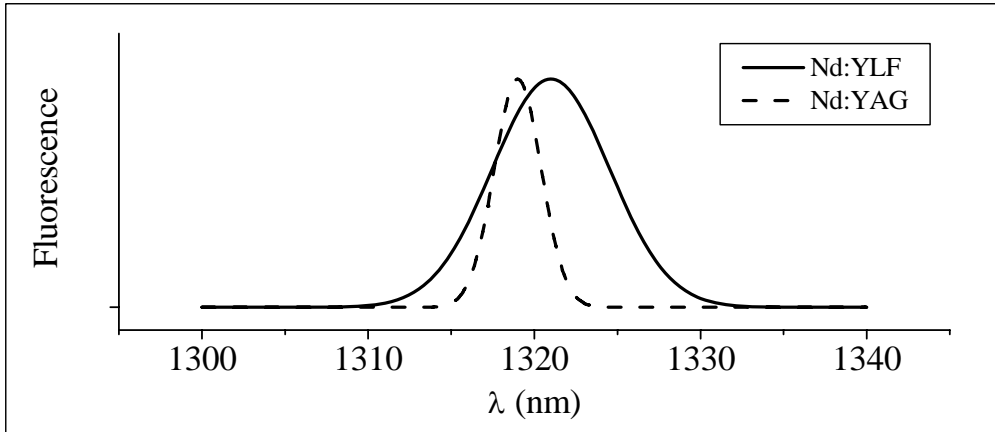


Fig. 4. Nd:YAG and Nd:YLF gain profile.

Coherent Technologies Inc has demonstrated up to 60W at 1.3  $\mu\text{m}$  for Gemini lasers<sup>22</sup>. The corresponding laser system is made of a mode lock oscillator followed by three amplifier stages pumped by 200W diode lasers per stage. The pulse format is a CW/mode-locked with 1 ns pulses separated by 12 ns. The beam quality is very good with a  $M^2 < 1.4$ . The spectral bandwidth is 1 GHz. This result is very encouraging for the production of high power at 330.3 nm.

#### 4.3 High repetition rate modeless Ti:Sa mixed with a 532 nm YAG laser

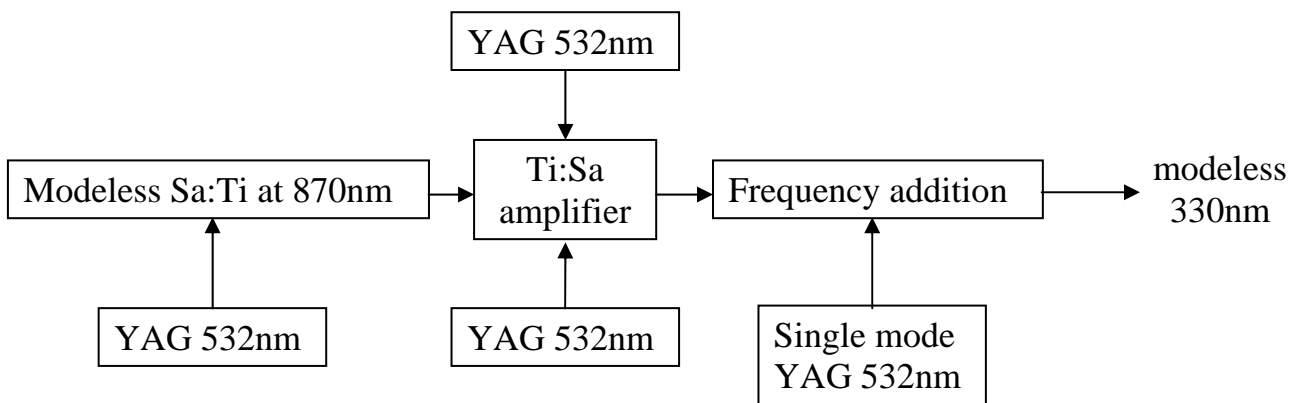


Fig. 5. Frequency addition of a 532nm Nd:YAG laser with a 870nm Sa:Ti laser for the production of 20 W at 330.3 nm.

Frequency addition of a 532nm Nd:YAG laser with a 870nm Sa:Ti laser is also an interesting solution for the production of the 330.3 nm laser line. Ultra high powers have been demonstrated for these two lasers operating in nanosecond and femtosecond regimes. Figure 5 above shows the set-up. 20 W at 330.3 nm are expected. 870 nm corresponds to the maximum gain of Ti:Sa laser amplifiers<sup>23</sup>.



#### 4.4 Flux versus laser repetition rate and PLGS spot size

The precision of tip-tilt correction using PLGS depends strongly on the artificial star size at the mesosphere. But, when its size decreases saturation problems start again to be a limitation. Solid state solutions we propose are interesting from this point of view as one can get higher repetition rate and pulse duration. Figure 6 below shows some examples using the model presented above.

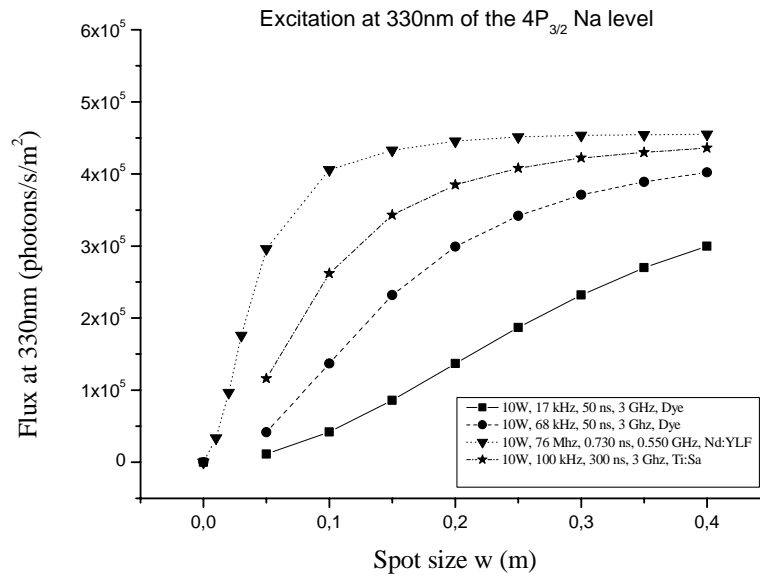


Fig. 6. Returned flux at 330 nm versus spot size for different laser situations.

#### 4.5 Rayleigh scattering

The Rayleigh scattering of the laser beam in the first 50 km of its propagation to the mesosphere raises some issues about the choice of the laser solution. Rayleigh scattering is a crucial problem since it gives unwanted photon noise on the wavefront sensor. It can be limited by sending the laser beam behind the secondary mirror of the telescope. However it will be a major limitation for multiple laser beams systems (MCAO) where it is not possible to occult all beams simultaneously. A solution to cancel the noise effects of Rayleigh scattering has been tested in our group and will be the subject of a publication to come. Namely it is based on the fact that the Rayleigh scattering is 100 % polarized and that the fluorescence of the sodium transitions induced by a modeless laser is almost completely depolarized, due to the hyperfine structure of the sodium atom. Thus by placing on the return path of the light an analyzer at 90 degrees from the direction of polarization of the laser beam, one can suppress completely the Rayleigh scattering and gain significant improvement of the signal to noise ratio (of course at the expense of loosing about 50 % of the fluorescence signal). Recall that the possibility of canceling the effects of the Rayleigh scattering is particularly interesting for UV atmospheric propagation (UV LIDAR, 330 nm-induced TTLGS...) since the intensity of the Rayleigh scattering evolves as  $\lambda^{-4}$ .

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