Pulsed laser architecture for enhancing backscatter from sodium

Thomas J. Kane*, Paul D. Hillman, Craig A. Denman
FASORtronics LLC, 1400 Eubank Blvd SE, Albuquerque, NM 87123-3340

ABSTRACT

The brightness of a laser-generated guide star is determined not only by the power of the laser, but also by the spectral and temporal properties of the laser. We show that a guide star laser pulsed at the Larmor frequency of the sodium atoms enhances guide star brightness by up to 2X, compared to an optimized cw laser at the same average power. We describe a frequency-addition source of optical radiation that can provide such pulsed light, while providing any desired spectral shape.

Keywords: Guide star, laser, pulsed, Q-switch, sodium, Larmor

1. INTRODUCTION

Next-generation ground-based telescopes require sophisticated adaptive optical systems, and a "guide star" laser is an essential component in these systems. The performance of the adaptive optical system, and thus of the telescope, depends on the amount of guide star light collected by the telescope, and thus on the brightness of the guide star created in the mesosphere. Models of sodium return show how to optimize return for a given level of laser power.[1]

1.1 Backscatter efficiency at low irradiance used as reference level

At a mesospheric irradiance level below 0.01 W/m^2, the laser does not perturb the distribution of sodium states, and the best return is achieved with a narrow spectrum exactly centered on the peak of the sodium line, at 589.159 nm. Under very low irradiance, laser polarization does not matter. The level of backscatter efficiency under this condition of very low irradiance will be used as a reference level. A goal is to maintain or exceed this level of efficiency over a wide range of laser irradiance, so that return signal rises linearly with laser power, or faster.

1.2 "Optical Pumping" with circularly polarized light enhances return

As the irradiance of the light in the sodium layer increases, it becomes advantageous to use circularly polarized light. Atoms that scatter circularly polarized photons move to angular momentum states which enhance their probability of backscattering subsequent photons. "Optical pumping" is the term often used for this beneficial redistribution of angular momentum states. Holzlöhner et. al.[2] showed that at a mesospheric sodium irradiance of 10 W/m^2 this effect can improve backscatter efficiency by a factor of 2, relative to the low-irradiance efficiency, for atoms that do not precess in the Earth's magnetic field. To achieve the benefits of optical pumping at the lowest possible irradiance, a laser with a linewidth below the lifetime-broadened sodium linewidth of 10 MHz is necessary, to ensure that the laser is interacting only with atoms in a narrow range of velocities. By interacting with fewer atoms, it is easier to significantly perturb their distribution of states, and to achieve the benefits of optical pumping.

1.3 Geomagnetic field substantially defeats the benefit of "Optical Pumping"

The benefits of optical pumping are substantially reduced when the atoms precess due to the geomagnetic field. The precessing atoms are reoriented in a time fast compared to the time it takes to establish a favorable distribution. Precession of the angular momentum imparted by laser photons does not occur when the laser beam is parallel to the magnetic field, and is maximized for the perpendicular case. Unfortunately, angles closer to perpendicular will be more typical. For the case of the beam perpendicular to the field, the benefit of optical pumping is almost completely eliminated.[2]

It would be desirable to find a way to maintain the benefit of optical pumping at all orientations of the laser and the magnetic field.

*tom@fasortronics.com; phone (505) 225-3733; fasortronics.com

Adaptive Optics Systems IV, edited by Enrico Marchetti, Laird M. Close,
Jean-Pierre Véran, Proc. of SPIE Vol. 9148, 91483G · © 2014 SPIE
CCC code: 0277-786X/14/$18 · doi: 10.1117/12.2055632

1.4 "Downpumping" reduces backscatter efficiency, but "Repumping" can defeat downpumping

Another effect, known as downpumping, results in reduced backscatter efficiency at higher irradiance. The sodium atom has two ground state energies, creating two distinct lines of absorption and emission, separated by 1.72 GHz. The stronger and redder line is referred to as the D_2a line, and the weaker and bluer as D_2b. If atoms are pumped only at the D_2a transition wavelength, the D_2a ground states will become partially depleted, as atoms accumulate in the lowest ground state that feeds only the D_2b line. This is "downpumping." Holzlöhner et. al.[2] showed that at 47 W/m^2 irradiance, downpumping can reduce backscatter efficiency by 70%, relative to the low-irradiance efficiency, for the "bad" magnetic orientation (field perpendicular to laser beam). The effects of downpumping can be ameliorated by also pumping the D_2b transition, a technique known as "repumping." Repumping has been accomplished by directing two distinct lasers at the same volume of the mesosphere[3], but it is more conveniently done by putting sidebands on a single laser, by phase modulation, intensity modulation, or ideally, a combination of the two, which would create a single, blue-shifted sideband. (If two sidebands are created, one will not interact with sodium at all, since it will be outside the Doppler width for both lines.) Holzlöhner et. al. showed that the optimum fraction of light at the D_2b wavelength is in the range 8-25%, depending on the strength of the magnetic field. At a cw irradiance of 47 W/m^2, for the "bad" magnetic orientation, repumping improves backscatter efficiency by 3.5X, bringing it back to the low-irradiance reference level.

1.5 At high irradiance, stimulated emission will reduce backscatter

Another effect that leads to lower backscatter efficiency occurs when a significant fraction of the sodium atoms are in the excited state. Atoms in the excited state will emit by stimulated emission, and two photons will uselessly travel into space. This effect, called saturation, leads to a 10% loss of efficiency at an irradiance of 46 W/m^2, for a laser linewidth well below 10 MHz. At higher irradiance, the loss of efficiency increases. The effects of saturation can be countered by broadening the linewidth of the laser. Holzlöhner et. al. evaluated the tradeoff between the good effect of optical pumping and the bad effect of saturation, and advises that the laser linewidth be broadened by 1 MHz for each 6 watts of laser power, for typical guide star spot sizes. At 20 watts cw, with optimum mesospheric beam size, the recommended laser linewidth of 3.3 MHz is below the 10 MHz sodium natural linewidth, so no observable effect is expected due to laser linewidth broadening. But as laser power increases, due to pulsing or larger average power, a broadened linewidth will be desired.

2. MODELING OF PULSED GUIDE STAR

2.1 "Magnetically Resonant Pumping" provides large benefit at most field orientations

Holzlöhner et. al. analyzed backscatter efficiency for cw guide star lasers. Using code developed by Rochester Scientific for the analysis of pulsed guide star lasers,[4] we have shown that by pulsing the laser at the magnetic precession frequency, often called the "Larmor frequency," it is possible to maintain the benefits of optical pumping regardless of magnetic field orientation. We call this technique for enhancing guide star backscatter efficiency "magnetically resonant pulsing."

For a typical geomagnetic field of 0.25 to 0.5 gauss, the Larmor frequency is between 175 and 350 kHz, linearly proportional to field magnitude. Magnetically resonant pulsing works because it substantially reduces the effect of precession, by allowing the atoms to interact with the laser light at a fixed point in the precession cycle, analogously to how a strobe light illuminating a rotating wheel can make it appear to stop. Subharmonics of the Larmor frequency are also usable, just as they would be in the strobe light analogy.

Figure 1 shows the results of our calculations. The vertical axis is the backscatter efficiency, in the units typically used. For reference, backscatter efficiency as irradiance approaches zero is 240, in the same units. The horizontal axis is the angle between the laser beam and the magnetic field. The upper trace, with red squares, is the case of magnetically resonant pumping, with other parameters optimized. The blue circles show the cw case, also with parameters optimized. For large angles, the benefit is a factor of two. Most telescopes will be operating in the 60°-90° range most of the time, since the magnetic field in the tropics is more nearly horizontal than vertical, and also due to the simple geometric fact that given any axis on a sphere, most of the sphere is more than 45° away from the axis.

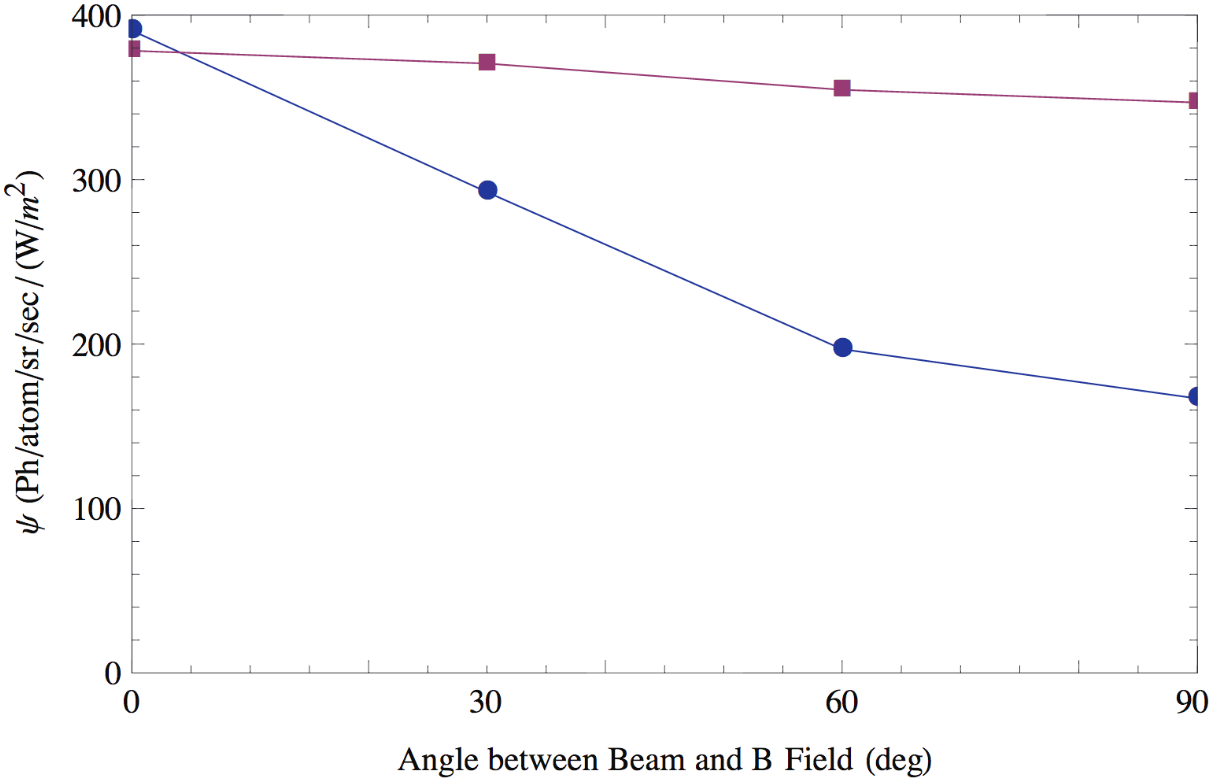

Figure 1. Backscatter efficiency as function of angle between laser beam and B field, calculated with pulsed model.
Red squares: Pulsed at Larmor frequency (350 kHz), 9% duty cycle, linewidth 150 MHz, D_2b fraction 9.2%.
Blue circles: cw, linewidth 9 MHz, D_2b fraction 15%.
Both: Average irradiance 47 W/m^2, B field 0.5 gauss.

Note that at an angle of 0°, the cw case is slightly better, because the broader linewidth of the pulsed laser reaches wavelengths farther out on the Doppler-broadened sodium line, where there are fewer atoms. But for the vast majority of possible orientations, the backscatter efficiency with the pulsed laser is better.

2.2 Countering "Recoil" with "Frequency Chirp" found not to be beneficial

One last technique for enhancing backscatter efficiency takes advantage of the fact that sodium atoms change velocity when they scatter a photon. This "recoil" effect depletes the number of atoms that are at the right velocity to scatter subsequent photons at the same wavelength. If the laser is chirped in wavelength toward the blue, it can reduce its interaction with the depleted velocity class, taking advantage of the enrichment of the velocity class receiving the recoiled atoms. The Rochester Scientific modeling code was augmented to allow the effects of wavelength chirping, sometimes called snowplowing, to be modeled. In this model, a sawtooth-shaped frequency chirp can be applied to the light interacting with the sodium atoms. We carried out calculations, which we will not present in any detail, since the main topic of this paper is the benefit of magnetically resonant pumping. The benefits of snowplowing are reduced as laser linewidth increases. But we found that the benefits of magnetically resonant pumping are lost due to saturation if the linewidth is not broadened, and thus the potential benefits of snowplowing must be foregone. Given a choice between magnetically resonant pumping and snowplowing, the former is much more valuable. The snowplow modeling code is available from Rochester Scientific.

3. FASOR ENABLES ALL TECHNIQUES FOR EFFICIENCY ENHANCEMENT

A FASOR is a Frequency Addition Source of Optical Radiation. Figure 2 shows a FASOR architecture that can provide pulsed light at the desired pulse repetition frequency and duty cycle for magnetically resonant pumping, while also providing a continuously variable linewidth, a single-sideband for D_2b excitation, and easy tunability, if chirping for snowplowing is desired. This design sums the 1319 nm and 1064 nm wavelengths of Nd:YAG in a crystal of lithium triborate (LBO), as do previous FASOR systems.[5] An important feature distinguishing this from previous FASOR architectures is that while the 1319-nm light is resonated, the 1064-nm light is not, and is converted in a single pass through the LBO.[6] The 1064-nm light can have any desired phase, frequency and amplitude modulation, unconstrained by the necessity of being resonant, and this modulation will also appear on the generated 589-nm light. The 1319-nm light is resonant within the laser resonator where it is generated. An acousto-optic Q-switch causes the 1319-nm light to be pulsed.

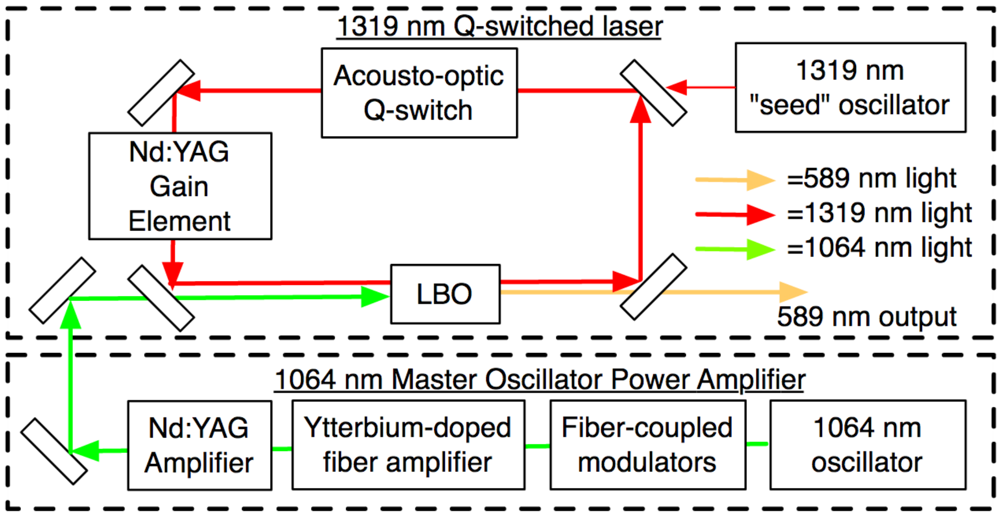

Figure 2. FASOR Architecture. 589 nm is generated by the summation of 1064 nm and 1319 nm in an LBO nonlinear crystal. The 1064-nm light makes a single pass through the LBO crystal. The 1319-nm light makes multiple passes through the LBO, since the LBO is internal to the 1319-nm laser resonator. 1319 nm is generated by a Nd:YAG laser, while 1064 nm is generated in an oscillator-amplifier chain.

The 1319-nm Q-switched laser oscillates at a single frequency due to injection-seeding by a low-power single-frequency cw oscillator, typically a nonplanar ring oscillator.[7] Injection-seeding of a Q-switched laser has considerably relaxed tolerances on power and frequency matching as compared to injection-locking of a cw laser.[8]

The modulated 1064-nm light is provided by an oscillator-modulator-amplifier chain. The oscillator is a single-frequency cw oscillator, again, typically a nonplanar ring oscillator. Conceptually, there are two phase modulators and two amplitude modulators, though in reality it may be better to combine signals in the RF domain and halve the number of optical modulators. Following modulation, the light is amplified. Most of the gain, and as much of the power as possible, is provided by fiber amplifiers. A final amplification stage in a bulk neodymium-doped gain element will be needed if peak output power is greater than 100 watts.

3.1 Modulation to achieve optimized spectrum

Figure 3 shows the function of the modulators. The modulators would be fiber-coupled, waveguide modulators of the type used in telecommunication systems. The first phase modulator receives electrical pulses that create phase modulation of either $+\pi/2$ or $-\pi/2$, with no dead time between pulses and a defined rate of pulsing. The sign of the phase of each pulse is random (or pseudo-random). Such randomly phased modulation will create light of a linewidth roughly equal to the defined rate of pulsing. Since fiber-coupled waveguide phase modulators can easily achieve modulation well above 1 GHz, the entire Doppler-broadened sodium line is accessible.

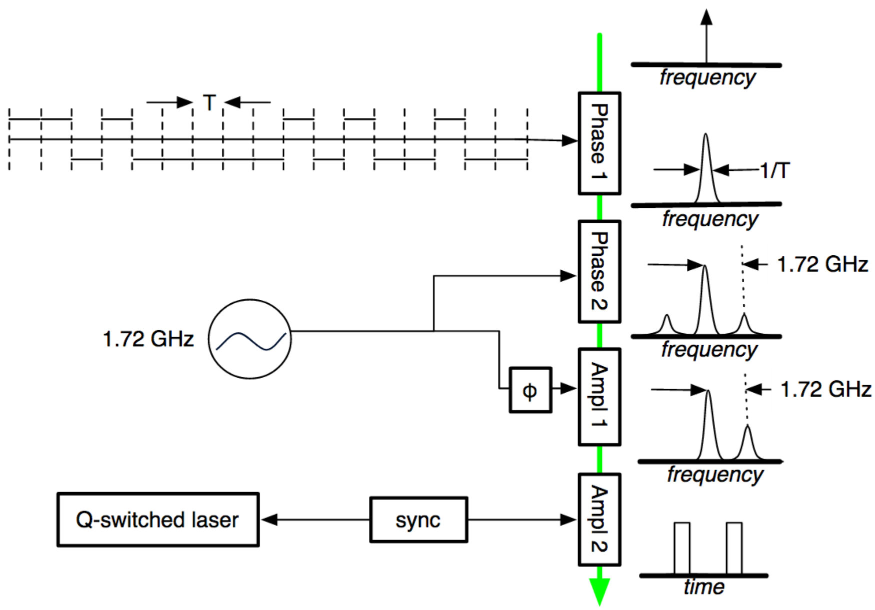

Figure 3. Modulators are fiber-coupled electro-optic waveguide modulators, such as are used for fiber communication. Signals could be combined in RF domain to halve the number needed. First modulator is driven by random pulses creating $\pm\pi/2$ phase shift. This broadens the linewidth. Second two modulators create a single sideband, blueshifted 1.72 GHz. Final modulator slices light into pulses at the Larmor frequency.

The second phase modulator is driven at 1.72 GHz, the frequency split between the D_2a line and the D_2b line. Phase modulation alone will place sidebands on both sides of the input. Since the desired amount of power in the D_2b line is about 9%, this leads to a waste of 9% of the power - since the red-shifted sideband is useless. By amplitude modulating the signal as well as phase modulating, at the same frequency and with a controlled phase difference, a single sideband can be created, blueshifted but not redshifted, saving 9%. This is the purpose of the first amplitude modulator.

The second amplitude modulator slices the light into pulses, synchronized with the pulses in the 1319-nm Q-switched laser, at a pulse repetition frequency that is adjusted to be at the peak of the magnetic resonance.

By placing the amplifiers after the modulators, all power lost to modulation is recovered at low cost. The power is then further amplified to a level adequate to efficiently extract power from the 1319-nm beam in the LBO. A final amplification stage using Nd:YAG or Nd:Vanadate bulk crystal amplifiers will be needed to reach peak power above 100 watts, which is the limit on the power of narrowband light in available fibers, due to stimulated Brillouin scattering. With a duty cycle of 9%, and assuming a 50% conversion of 1064 nm, a 20 watt average power 589-nm laser will require 22 watts of 1064 nm average power, and a peak power at 1064 nm of 242 watts. Thus a single final-stage neodymium bulk amplifier with a gain of 3X puts the fiber amplifier into a safe power range. This is not a challenging level of gain for neodymium bulk amplifiers. The Nd:YAG amplifier used for the Laser Interferometer Gravitational Wave Observatory (LIGO) had a gain of 28.5X, with an output power of 20 watts.[9]

The architecture we have presented enables four techniques for return efficiency enhancement - D_2b re-pumping, magnetically resonant pumping, linewidth optimization, and, if desired, "snowplowing" for recoil compensation, although we do not expect the latter to be valuable when the laser linewidth is increased as needed for pulsed operation.

4. PRELIMINARY EXPERIMENTAL RESULTS

A concern with this design is the low gain of Nd:YAG at the 1319-nm wavelength. Low gain makes Q-switching at a high repetition rate difficult. To verify that gain was adequate, we built a 1319-nm acousto-optically Q-switched laser using a single side-pumped Nd:YAG gain element. This laser was operable at pulse repetition rates up to 350 kHz, which is on the high side of what is necessary to reach the sodium Larmor frequency, which varies with geographical location. Figure 4 shows an oscilloscope trace for this laser, with the Q-switch operated at 350 kHz, corresponding to a time between pulses of 2.86 μsec. The pulse duration FWHM is 0.18 μsec, for a duty cycle of 6.3%, near the 9% value used for the calculations of Fig. 1.

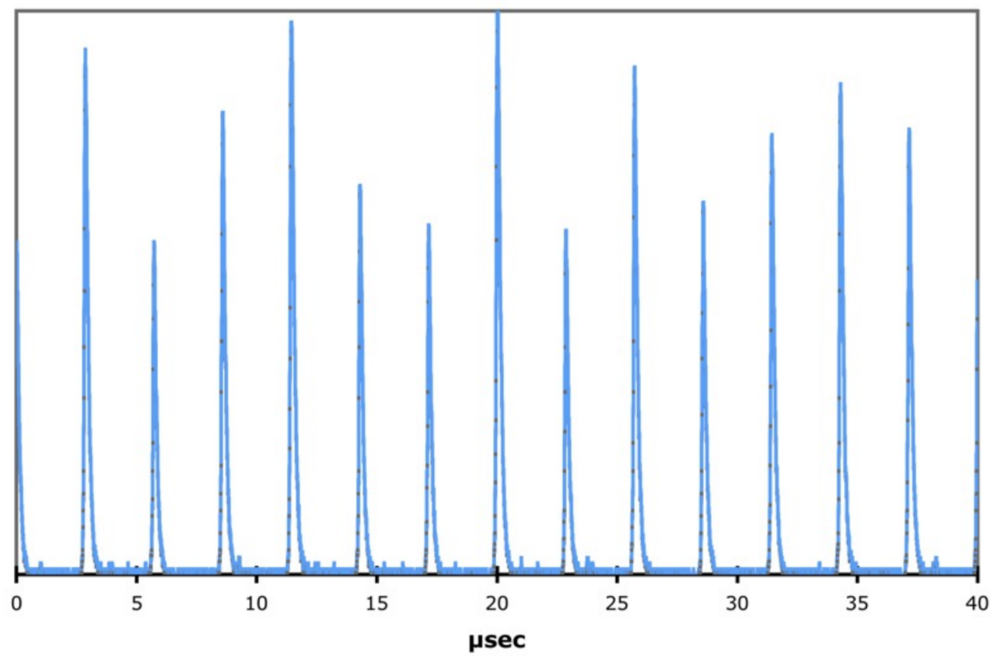

Figure 4. Oscilloscope trace of 1319-nm acousto-optically Q-switched laser. Pulse repetition frequency is 350 kHz, pulse duration FWHM is 0.18 μsec.

The pulse-to-pulse variation in Fig. 4 may be improved by injection-seeding, which stabilizes the pulses. Pulse-to-pulse stability is not critical, as long as pulse timing is maintained at the Larmor frequency, which is easily accomplished.

5. CONCLUSIONS

We have shown by calculation that a guide star laser pulsed at the Larmor frequency can have enhanced return efficiency compared to an optimized cw system, over almost all orientations of the magnetic field. For magnetic fields perpendicular to the laser propagation direction, the enhancement is a factor of two.

We have proposed a FASOR (Frequency Addition Source of Optical Radiation) architecture that we believe can provide this pulsed format, while also providing a variable linewidth to avoid saturation, and a single sideband for repumping.

We are confident that FASOR systems using the hybrid bulk crystal / fiber architecture we have described can reach an average power of 50 watts. It is exciting to realize that at this high power level, the backscatter efficiency of the sodium layer is not expected to drop off, but instead, when averaged over all magnetic field orientations, will be above the level achieved by any previous guide star laser at any power.

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