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Firing a Laser into the Sky Diverts Lightning Offering Greater Protection to Installations

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Abstract

Lightning bolts cause thousands of deaths every year worldwide. Since Benjamin Franklin's invention of lightning rods made almost 300 years ago, the technology has not been changed even today. The same Franklin lightning rods are used on top of the buildings to steer lightning down to the ground so that they don't pass through the buildings, and damage the structure or electrocute people. Researchers have recently developed a new type of lightning protection system called laser lightning rod (LLR) that uses powerful laser which is fired rapidly in the air during thunderstorms. An electrical current can flow via the plasma channel formed in the air by the strong laser beam. The channel of ionized air thus produced can be focussed on top of a conventional lightning rod installed at a secured location away from the vital installations to be protected, and extended to the thunderstorm cloud. The advantage is that the laser can steer lightning over a much wider area, because the virtual height of LLR is increased quite a bit. The LLR then deflects and directs lightning away from the vulnerable installations safely to ground through the conventional lightning rod located at a safe distance away from the installations to be protected. Moreover, the precision of the laser allows for real-time adjustments, ensuring optimal protection during varying storm conditions. The LLR system can be integrated with weather monitoring technology to predict and react to potential lightning strikes more effectively.

Keywords: Laser, Femtosecond, Filamentation, Chirped pulse amplification. Multipass amplifier, Pulse recompression

INTRODUCTION

Figure 1 shows violent lightning strikes spread over a vast area, which can damage structures and threaten human life. The core temperature of lightning is about 28,000°C. A typical lightning strike may have 300 million volt and 30,000 amp. These adverse conditions cause extensive damage of properties and life. World wise death rate due to thunderbolt is estimated to be about 24,000 human lives, and in India in 2020–2021 about 1619 people were killed [1]. Currently, protection against lightning strikes is done by lightning rods, an 18th century invention of Benjamin Franklin, which is a long metal rod placed on the top of the structure and rooted to the ground through a conducting aluminium or copper stripe. The metal's conductivity lures the lightning bolts that are often five-times hotter than the sun's surface that might otherwise damage life and property and feeding that electricity safely to the earth. But these physical rods can only shield a limited area. If a building has a ten-metre-high traditional lightning rod, it protects a region with a radius of about 10 metres, which may be fine for that building, but not sufficient for an airport or rocket launching complex or a wind farm, that may be a few kilometres long. For

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protection of such complex, a lightning rod of kilometre size would be required, erection of which

Figure 1. A typical violent lightning strike.

is not possible in practice. But a laser could reach that far and lure the lightning to ground saving the complex of buildings. Particles that are charged and moving from one place to another create lightning. The majority of particles in clouds are charged particles. The water droplets travel downhill, and the air currents move upward during a thunderstorm. This movement causes the positive charges to gather close to the cloud's upper edge and the negative charges to gather close to the cloud's lower edge as well as the ground. The charge grows increasingly huge in magnitude as it accumulates. Droplets of water in the atmosphere conduct this charge. The air's ability to act as an insulator is compromised when the opposing charges accumulate to a certain point, resulting in a lightning bolt. The path that this current takes will be the most electrically conductive. Even if the clouds over thunderstorms are very high, nevertheless This creates a path made of lower density air that contains electrons released by oxygen and nitrogen of air that are free to move. This ionized air channel is conductive, and channels the lightning along this path of least resistance to the ground. So the researchers thought, why not replace the Franklin lightning rod with a laser that is a kind of longer virtual rod, and can be directed easily to any direction, and at any time as per requirement [4].

WHAT IS LASER

The word "laser, in which the cavity contains a ruby crystal (item 5). An aluminum oxide crystal with some of the aluminum ions replaced with chromium ions is called a ruby. A solid state laser, sometimes known as a ruby laser, has a wavelength of 694 nm.

A laser consists of a chamber known as cavity, which can contain either solid, liquid, or gas, and its material of construction determines the wavelength of the laser. Figure 2 shows the construction of a ruby laser, where a ruby crystal is housed in the cavity (item 5). A ruby is an aluminum oxide crystal in which some of the aluminum ions have been swapped out for chromium ions. The wavelength of a solid state laser, or ruby laser, is 694 nm. Mirrors are placed on the two ends of the cavity. One of the mirrors (item 6) is totally reflecting, and does not allow to pass any light through it. The other mirror (item 7) on the opposite end is semi- transparent, allowing about 5% of light energy to pass through it. A helical xenon flash tube (item 2) encircles the ruby rod and supplies the pumping light needed to elevate the chromium ions to an upper energy level. Each flash in the xenon flash tube lasts for several milliseconds and provides the ruby laser medium's atoms (item 3) with a few thousand joules of energy. The ruby crystal's lower energy state electrons transition into the higher energy state when they get enough energy

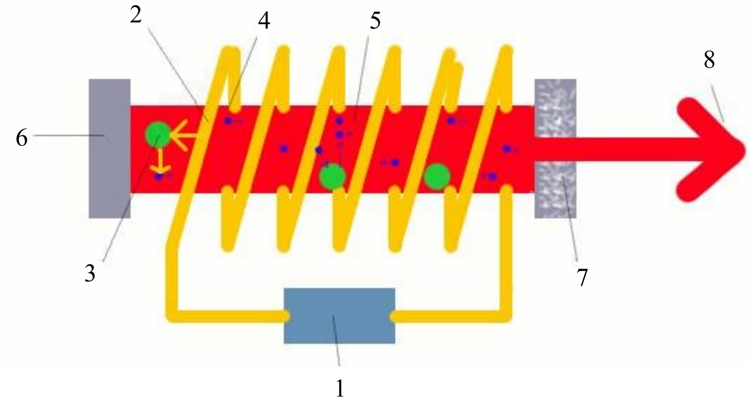


Figure 2. Schematic diagram of a ruby laser.

from the flash tube. condition of energy or excitement. The lifetime of an electron is the amount of time it can remain in its excited state. As a result, following their brief lifetime of excitement, the excited electrons swiftly transition to a slightly lower energy level by emitting photons, which are represented as tiny blue blobs in Figure 2. In a laser, excited electrons don't have to wait for their lifetime to end thanks to a process known as stimulated emission. Rather, the excited electrons are forced to revert to the ground state by the interaction between the incident photon and the electrons. As it descends to the ground state, this excited electron releases energy in the form of light. Two photons are released during stimulated emission, The escaping photons coming out through the partial mirror (item 7) form a very concentrated beam of coherent laser light (Arrow 8).

OVERVIEW OF LIGHTNING RESEARCH AT MOUNT SANTIS

At 2502 metres, Santis is the highest mountain in the Alps of Switzerland, where there is a 124 m tall communication tower. The Swiss built a weather station on Santis in 1882. The Santis tower faces most lightning strikes in Europe, some 100 times a year. This makes the tower very suitable for collecting data on lightning. So researchers conduct research work about lightning in this weather station. Since 2021 a team of researchers has been investigating, and developing a new technique of lightning protection using high powered multi-terawatt laser.

But, in practice it was found that high powered lasers failed to perform because, within a short distance the ionized air simply absorbed the laser light, leaving the air channel not conductive enough to attract thunder. Researchers created lasers in the 1990s that could generate pulses as short as femtoseconds. The new type of laser will produce a long ionized channel in the cloud called a laser filament that is the width of a hair by releasing 1000 ultrashort laser pulses into the atmosphere per second. The light is further focused into a longer “filament” by the ionized air acting as a lens. These shorter, lower energy pulses proved more effective at opening conductive channels. The laser filament will act as a preferential path with least resistance to electrical conduction, and divert lightning away from vulnerable sites. The thin beam heats the air, driving away molecules and leaving a channel of lower density air, which provides better conductions for electric current flow.

At the top of Santis mountain, Switzerland at an altitude of 2481 m there is a 123 m tall radio/TV transmitting station equipped with a conventional lightning rod, which also has been used for lightning research purpose. Researchers installed laser assisted lightning rod (LLR) at the very summit of Mount Santis and operated it in conjunction with the normal lightning rod. The LLR (measuring 1.5m wide X 8 m long) weighs more than three tons. LLR, and its accessories like electrical surge protection device, copper/aluminium low impedence earthing cable to disperse the energy safely to the ground are designed to protect a group of installations from a direct lightning strike. It may be noted that the system does not prevent lightning from striking buildings, but rather intercepts a lightning strike and conducts it through the path of least resistance of hair thin filament zone in the air, and then safely to the ground through copper/aluminium earthing cable. During research work scientists found that if laser with sufficient intensity is fired at a repetition rate of 1 kHz, and focussed at a point near the the laser pulse experiences self-focusing at the top of the transmission tower atop Santis Mountain, continuously condensing the laser power into a more intense pulse and creating a plasma filament along the laser's path. This filament can successfully guide thunderbolt for about 60 m before reaching the tower. This means that the range of protection has been increased from 123 m (height of the tower) + 60 m i.e. 183 m. That is a big step. However most lightning channels are kilometres long. Therefore, the capability of laser and its range is to be increased, which is a difficult task, but not impossible. There is another obstacle that is to be overcome. Unlike conventional Franklin lightning arrestor which works round the clock, LLR can not work continuously, because high powered laser causes injury to people flying in a plane, and can damage the plane. Once the LLR is switched off the conductive filament path also is collapsed. So it is necessary to switch on the LLR before the onset of thunderstorm. Researchers have now created an inexpensive hindcasting system using machine learning techniques that can predict 30 minutes in advance, when lightning can strike inside a 30-kilometre radius. To do this the researchers collected weather conditions of the site which is to be protected, like air pressure, air temperature, relative humidity, and wind speed for the last ten years. The data on weather condition for the last couple of years are fed to the computer. Letting the computer discover relationship between weather variables, and lightning bolts, it is possible to build an algorithm that could predict about impending lightning strike. This simple and cheap model can predict new lightning strikes with an accuracy of 80%. Such lightning forecasts model based on artificial intelligence can be integrated with laser lightning rod enabling LLR to be activated well in advance before the lightning strikes [2].

LASER SYSTEM

During the experimental campaign at Santis Mountain it was found that the most suitable system was Yb:YAG chirped pulse amplification (CPA) laser system developed by TRUMPF Scientific Lasers. A chirp refers to a phenomenon where the frequency of a laser suddenly increases or decreases with time. If we try to pump too much energy into a laser, the power density level may be too high to melt the equipment. High power laser pulse in GW/sq. cm, if allowed to travel in the laser medium would immediately self-focus, form a plasma, and damage the laser components including optics. Using the chirped pulse amplification (CPA) approach, this issue can be resolved. Through the use of this technique, light is first diluted and then amplified to a greater overall strength without reaching a dangerous intensity. In this method, firstly with the help of a prism or a diffraction grating, short laser input pulse of light is decomposed into all its constituent colours, and then the longer wavelengths is sent first, and the shorter wavelengths last. This problem can be handled by using the chirped pulse amplification (CPA) technique. This method amplifies light to a greater overall strength without reaching a harmful intensity by first diluting it. The lower intensity pulse is then amplified in the laser amplifier to a safe level. Finally, the pulse is sent through a reversed set of gratings that cancel the relative delay between the shorter and longer wavelengths, and adding them together into a single pulse of higher power with the same optical characteristics of the input light. In this way it is possible to get an equipment melting amount of power in the laser beam without melting the device. CPA laser can deliver a short laser pulse of petawatt range, and the time of pulse can be as low as a femtosecond. The CPA laser system, which is typically utilized in LLR research, can currently produce a filament with a length of more than 70 meters by producing a consistent 720 mJ of pulse energy at a pulse duration of 920 fs at a repetition rate of 1 kHz. This results in a peak power of 690 GW. It is possible to extend the filament length even more by using a magnifying telescope. However, the pulse duration is kept at roughly 7000 fs, and the output energy is restricted to 500 mJ to avoid damaging the optics [3].

Chirped Pulse Amplification (CPA)

Ti: For a very long time, researchers have been using Sa lasers. However, there are some disadvantages. This method can be used to create a tiny tabletop terawatt laser that can produce millijoule-energy pulses with femtosecond durations that can result in several terawatts of peak power.

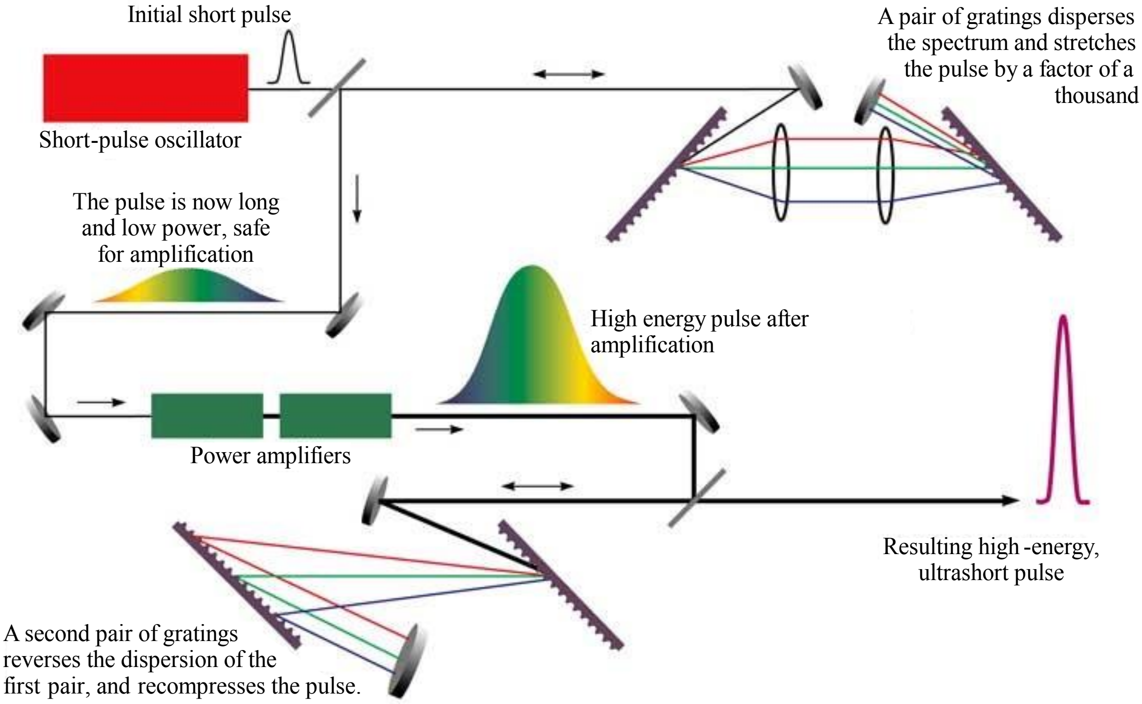


Figure 3. A simplified diagram of CPA laser.

CPA lasers is a very useful tool for LLR. It uses diffraction gratings for stretching or compressing laser pulse length. The gratings are made of monolithic fused silica with high laser induced damage threshold, or it can be made of metal. A simplified diagram of CPA laser is shown in Figure 3 For a very long time, researchers have been using Sa lasers. However, there are some disadvantages. Once all the frequencies are amplified, they are recombined in a second pair of gratings, thus total power of each frequencies are added together to make a powerful laser avoiding any damage to the lasing device (5).

LASER SYSTEM OF LLR USED IN MOUNT SANTIS OBSERVATORY

Schematic diagram of CPA laser system used in laser lightning rod in mount Santis observatory is shown in Figure 4. Ti: Sa lasers have been used by researchers for a very long period. But there are certain drawbacks. It requires precise alignment and control of pump laser, the crystals, and the mode locking device which make it more expensive and less reliable. These lasers have limited average output power to a few watts, which can not meet the power demand of LLR. 30% quantum defects often found in Ti: sapphire crystals, make them hot during operation, requiring complex cooling mechanism. Its radiative lifetime is as short as 3-4 miro-second. To circumvent this problem complex and costly pumping method at 500 nm is required. Yb-doped laser crystals, like Ytterbium-doped yttrium aluminium garnet (Yb:YAG) have lot of advantages and are now preferred for fabrication of high powered lasers, providing kilowatts of optical power at main absorption band of 940 nm. It has low quantum defect of about 9% and therefore generate very low heat. It has excellent thermal conductivity of 11.2 W/mK. Its upper-state life time of about 1-2 ms, which is relatively long, is suitable for Q-switching, and for pulsed switching used in CPA laser. Its upper state lifetime is very convenient for continuous wave pumping, and operating at higher power level. The laser device at mount Santis comprises of the following sub-units with certain special features.

Thin Disk Geometry

CPA lasers are well suited to thin-film laser technology, which produces high pulse energies up to the Joule level and repetition rates of kHz. As illustrated in Figure 5, a thin disk laser is a kind of solid state laser in which the gain medium is made up of thin disks, usually made of Yb:YAG crystal, with a thickness of 150 to 200 µm, which is significantly less than the beam diameter. This feature allows not

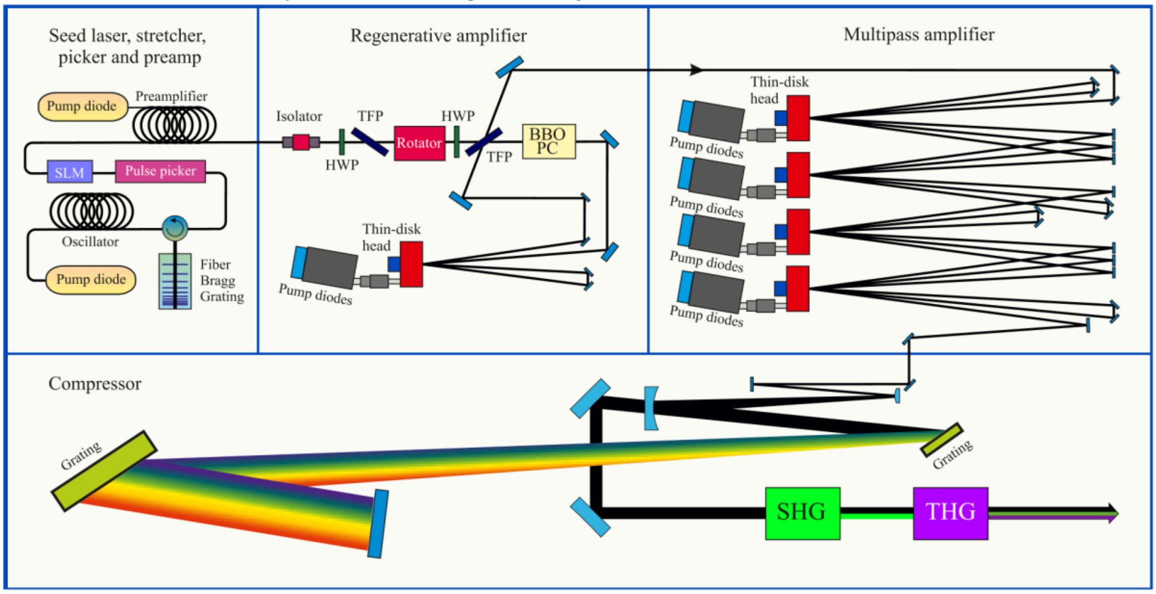


Figure 4. CPA laser system used in laser lightning ROD.

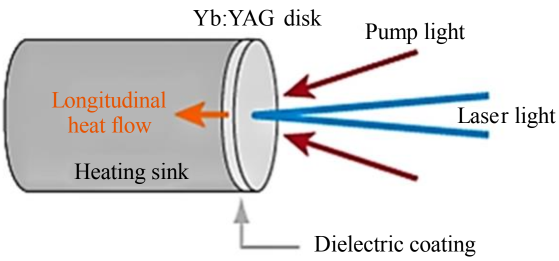


Figure 5. Schematic set up of a thin disc laser head.

only the ability to scale up power, but also cooling the laser very efficiently. For thin disk geometry the procedure for power scalability is very straightforward. If it is required to double the rated power, just increase the cross section of the disk twice keeping the disk thickness, and doping level same, and then double pump power [5]. The disk surface is mounted on a diamond or copper heat sink which efficiently takes out heat longitudinally. The back surface, mounted on the heatsink, is coated to reflect both the pump, and the laser radiation. The thin disk geometry provided in CPA lasers has made these lasers suitable for high power scaling, providing multi-kilowatt laser output power, and there is no thermal lensing. This technology provides high-quality beam at high power levels up to 4 kW in the fundamental mode, and up to 16kW in multimode operation with power conversion efficiency of about 70%, and is now commercially available [8] In conventional lasers using laser rods as active material, the heat dissipation is a major challenge. Cooling the rod via its surface is rather inefficient due to the large volume to surface ratio. Additionally, it generates a temperature gradient perpendicular to the laser axis which results in thermal lensing. The use of a thin disk that is cooled from one side is the logical step towards better cooling, and that results in getting higher output power [6].

Regenerative and Multi-pass Filter

A high powered CPA laser system generally uses a seed laser as the starting point as shown in Figure 4, and other sub-units as explained below. The system used in LLR at mount Santis consists of two main amplifier stages, e.g. a regenerative amplifier followed by a high energy multipass amplifier.

Both these amplifiers are designed by TRUMPF, Germany using thin disk technology. The laser unit is wheel mounted enabling it to move from place to place, and is about 8.2 m long, and 1.4 m in width. There is no need to cryogenic cooling or vacuum pump, as it operates at room temperature, and at atmospheric pressure.

Seed Laser

Typical types of seed lasers may be small laser diodes, or short-cavity fibre lasers, or miniature solid state lasers. It typically generates femtosecond pulses at 1030 nm with average power of about 100 µJ at a repetition rate of 1 kHz. The seed laser is provided with a chirped fibre Bragg grating that stretches the ultrashort pulses to a duration of 1 ns, and preamplified in an active fibre. Instead of using a single high powered laser, it is preferable to use low powered seed laser, because it provides a stable single frequency ultrashort pulse with narrow bandwidth. Tuning of wavelength over a wide range is also possible.

Regenerative Amplifier

The preamplified pulses from the seed lasing module are fed to the next module of regenerative amplifier, which acts as a first high powered amplifying stage. Regenerative amplifier mainly consists of an optical resonator that provides multiple passes, a gain medium provides amplification, and an electro-optic switch admit weak input pulses and releases amplified pulses like a valve. The electro-optic switch comprises of a Pockels cell, a quarter wave plate, and a polarizer. Low Q state of the resonator and large intracavity losses result from the wave plate and polarizer working together when the Pockels cell is not receiving voltage. The laser action is suppressed by this phenomena. However, because the gain medium is constantly being pumped, population inversion is building up. The optical pulse cycling in the resonator is amplified to the required level in the subsequent cycle when the Pockels cell is subjected to a quarter wave voltage and the seed pulse is injected into the resonator. At that moment, the amplified pulses exit the cavity and the Pockels cell voltage is turned off. as the output pulses. The regenerative amplifier is of model Dira 200-1, made by Trumpf Scientific Lasers Gmbh. It is provided with a thin disk laser head that is pumped by 940 nm laser diodes with up to 1kW average pump power. Coupling of incoming, and outgoing pulses is done by a BBO-based Pockels cell in association with a thin film polariser (TFP). The pulse energy is boosted to 240 mJ within multiple resonator roundtrips. With the help of the feedback from an internal diode the output energy is stabilized [7].

Multipass Amplifier

The boosted up pulses from the regenerative amplifier is next sent to the multipass amplifier for further amplification. Four thin disk laser heads, each with a 940 nm wavelength and the capacity to handle up to 10 kW of pump power, are included with the multipass amplifier. Typically, each disk is pushed with 2.3 kW of electricity. Two stages of amplifying the pulses are used. In the first step, eight passes through the first two laser heads are used to increase the pulses' energy from 240 mJ to 550 mJ. In the second stage the remaining two thin disk laser heads provide additional four disk reflections, and boost the pulse energy to 800 mJ. Curved parabolic mirrors, and prism retro reflectors are placed between two disks of each stage that reduce the overall propagation distance. Moreover, this arrangement facilitates 8 or 16 double passes of the pump radiation comfortably. Each disk is pumped, generally with high powered diode bars, with about 2.3 kW of power i.e. about 9 kW of total power.

Pulse Recompression

Final stage is recompression stage, where pulse recompression is done through a reversed set of gratings. These gratings cancel the relative delay between shorter and longer wavelengths, and by adding them together it is possible to get a single pulse of femtosecond duration, and of higher power in petawatt range without melting the costly laser device. The LLR research work is at present using stable pulse energy of 720 mJ, at 920 fs, and at 1kHz repetition rate that leads to a peak power of 690 GW. Experiment at Santis observatory shows that such laser system can provide a filament upto 70 m long. However, considering safety of the equipments, the output energy is limited to 500mJ, and pulse duration at about 7000 fs.

EXPERIMENTAL CAMPAIGN

Lightning has fascinated and terrified mankind since immortal. It is estimated that there are about 120 flashes per second world wide causing considerable damage. Therefore, it is critical to have an improved system in place to protect against this natural occurrence. Therefore, it would be ideal to have

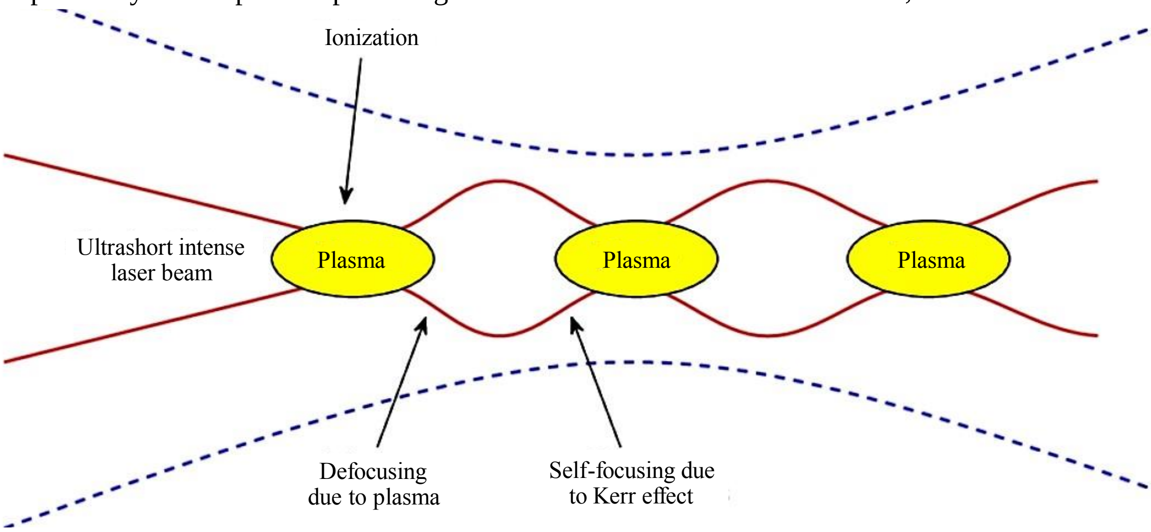


Figure 6. Filamentation process.

a method that securely triggers and guides natural lightning that runs continually. The initial test, which used a lengthy laser pulse lasting several nanoseconds, was conducted in the 1970s and was ineffective. This strategy was abandoned because electron avalanche caused the plasma generated by such a long IR pulse to have a discontinuous profile and because it took a significant amount of laser energy to generate a plasma column that extended beyond a few meters. Sub-100 fs laser pulses are discovered to be sufficiently brief to stop an electron avalanche. Because of this, the produced plasma is still transparent to the laser pulse, allowing for the ionization of self-guided filaments that are longer than 100 meters. The ability of an extremely powerful ultrashort laser pulse to maintain focus over a long distance is known as filamentation. In the atmosphere, sedimentation starts the process of creating an air-depleted low-density channel. When air density was reduced by a factor of five over a few meters in the air, a multi-TW laser's low density channel favored the triggering and guiding of electric discharges in the atmosphere with a 60% decreased voltage. An cumulative impact increases the air density depletion caused by filamentation at repetition rates in the kHz range. As illustrated in Figure 6, laser-induced filamentation is a nonlinear optical process in which powerful laser pulses self-focus due to the Kerr effect to overcome pulse diffraction and transmit distances significantly longer than the diffraction length while keeping a tight beam width. A terawatt laser with a 100mJ, 1030 nm, and 1 kHz repetition rate can decrease the breakdown voltage by a factor of three, enabling the creation of a long-lasting low density channel that can direct lightning strikes. The air is quickly heated by the absorbed laser energy along these filamentary regions and then evacuated at supersonic speed, leaving behind long-lasting, low-density air channels. Because of their increased electronic conductivity, these low density channels with millisecond lifetimes offer an electrical discharge path with low resistance. It is possible to remotely control the filamentation process to start it a kilometer from the laser source and safely cause lightning discharges to hit the planet [9].

At the summit of Santis Mountain in Switzerland in 2021, Laser Company Trumpf and the University of Geneva ignited a laser-powered lightning rod. Their goal is to regulate lightning that originates from storm clouds and steer it away from areas of potential danger. As shown in Figure 7, in order to comply with environmental requirement, the laser is located in a radome, 20 m away from the tower sheltered in an air- conditioned air tight polyester tent where temperature is maintained around 20^0 C and at 50% relative humidity. The 200 mm diameter metal tube that passes through the radome skin guides the laser output beam through the skin and into an isolated aluminum housing. A 100 mm folding mirror then focuses the beam into a 7.14 magnification beam expanding transmitting telescope. The final beam diameter, which is 250 mm, concentrates near the top of the tower. In order to reach the top of the tower, the telescope's construction ensures that the beam departure meets the 70-degree angle. Focusing control adjusts the filament onset distance.

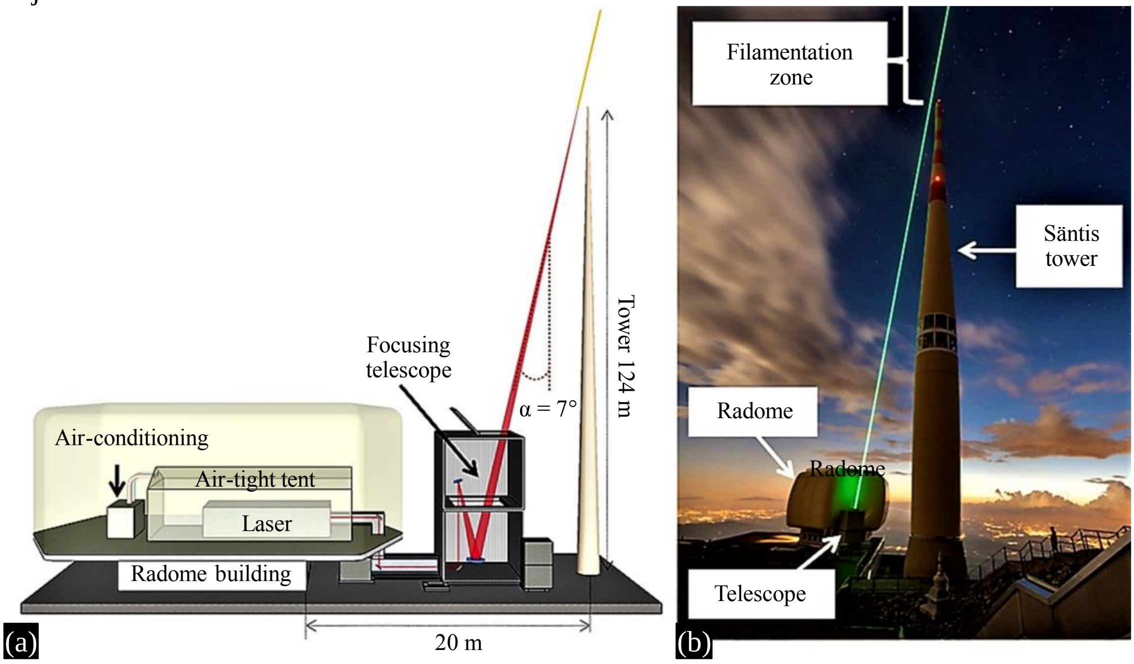
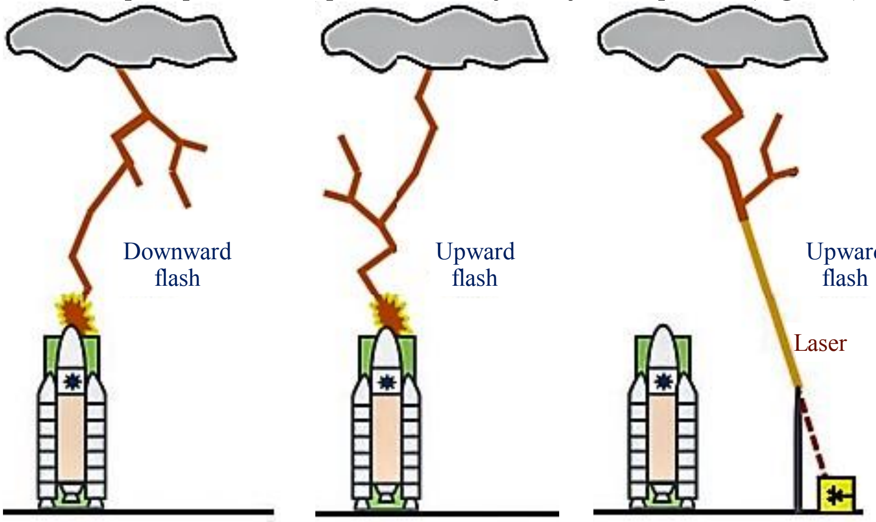


Figure 7. Experimental laser ligtning rod set up at santis.

Figure 8. Path of lightning strike through filament tube.

How the system functions about 1000 times each second, the laser sprays brief, powerful bursts of infrared light at the clouds. Roughly a terra-watt, or one million million watts, of immediate energy is carried by each pulse. Only a very short period of time, roughly a picosecond, can this quantity of energy be supplied. A moving line segment makes up the pulse. This process of optical nature is nonlinear. As the pulse gets smaller, its power density rises, intensifying the effect and generating a feedback loop. The pulse of the laser self-focuses. The air itself functions as a stronger lens, continuously compressing the laser power into a pulse with more intensity. This goes on until the air becomes ionized, or when the air's electrons split apart to form plasmaThe way the system operates (Figure 8).



In the Laser Lightning Rod project, upward lightning flashes will be initiated by a high-repetition-rate, multi-terawatt, directing lightning away from vulnerable objects.

Figure 9. Diversion of lightning by LLR to conventional ligtning arrestor.

The researchers used their lasers for a total of 6 hours over the course of two months, during which time the tower sustained multiple lightning hits. It was verified that, during the system's operation, laser-induced filaments successfully steered four out of the four lightning impacts based on high-speed photography and radio emissions from lightning discharges. The laser route was followed by these hits. As shown in Figure 9, harmful lightning strikes can be conveniently diverted with the help of LLR to a secure location where a conventional lightning rod is installed and the powerful lightning instead of striking the vital installation like rocket launching pad would be safely discharged to the ground [8-10].

CONCLUSION

A potential technology is the laser lightning rod. The experimental campaign's findings show that the laser can affect a lightning strike's path as it approaches a frequently hit target, such as the Santis tower. The next stage is to demonstrate how a laser may draw fire from a thunderstorm to create lightning and safeguard vulnerable facilities that are dispersed across a large area. To do this, a more potent laser would be required in order to create a plasma channel that reaches at least 500 meters into the sky. A lightning rod with such a tall laser may direct lightning away from delicate structures like airports, wind farms, or rocket launch sites. Forecasting lightning strike well in advance is a technical necessity, and also necessary for safety of air traffic, for which artificial intelligence is to be developed further.

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