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Ultraviolet UV lasers for aerospace wire marking

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Summary

This report discusses ultraviolet (UV) lasers in relation to the development of UV laser wire marking of aerospace wires and cables. The key characteristics of UV lasers suitable for this application are defined in terms of the mark process requirements (laser wavelength, pulse length and applied fluence) and operational requirements (laser pulse repetition rate). The mark process requirements for UV laser marking are:

Laser wavelength:	200-380 nm
Pulse length:	< 35ns
Applied fluence	~ 1 Jcm^{-2}

Two classes of UV lasers that meet the general requirements for wire marking are discussed. Excimer gas lasers operate at a number of discrete wavelengths throughout the UV and include the 308 nm Xenon Chloride laser, which was the first UV laser to be used in a production aerospace wire marking system. Lower average power UV solid state lasers based upon the frequency tripled Neodymium YAG laser (Nd YAG), which operates at a wavelength of 355nm, have also recently been introduced for this application. Both provide high quality non-aggressive marking.

Background

The use of short pulse ultraviolet (UV) lasers for aerospace wire marking is now a well established and accepted process. Laser marking is non-aggressive and creates high quality, highly legible and permanent marks on modern aerospace fluoropolymer insulations; e.g. polytetrafluoroethylene (PTFE), ethylenetetrafluoroethylene copolymer (ETFE), fluorinated ethylene propylene (FEP). It may also be applied to other insulation media.

The initial discovery and development of UV laser wire marking was carried out and reported on by co-workers from British Aerospace during 1987/1988 [1]. During this initial work a variety of UV lasers were investigated for their effectiveness in marking aerospace wires. The net result of these investigations defined the general requirements for UV laser marking as follows:

1. Laser wavelength: Typically 200 to 380nm (1nm = 10^{-9} m)

   Short wavelength UV laser light is required to create a mark without causing undesirable side effects, i.e. damage to the wire. Damage is defined specifically as an unacceptable and deleterious change in the wire insulation's mechanical or electrical properties.

   The wavelength range noted spans the whole of the UV, from the deep ultraviolet, 200nm, to the near visible, 380nm. Lasers with wavelengths in the range 193nm to 355nm have been investigated for wire marking. It was found that the fluoropolymer insulations investigated were *not* strongly sensitive to wavelength. Within the limitations of equipment available, *any* wavelength in the UV region was found to be effective.

   NB. Long wavelength infrared (IR) lasers are not suited to marking standard wires, but may be used with some specially manufactured duplex coated wires.

2 Laser pulse length: Typically <35ns (1ns = 10^{-9} seconds)

   The laser pulse length is a critical parameter in achieving the desired marking process. Very long pulse lasers or continuous wave, CW, (non pulsed) lasers either do not produce a mark at all, or produce a poor quality mark.

   It was found necessary to use short pulse lasers to generate a good mark. Lasers with pulse lengths < 35ns were found to be suitable. The cut off is not hard and fast, and is more to do with the lack of lasers with pulse lengths in the range 35 - 1000ns. However, the point is somewhat academic.

   Lasers with pulse lengths as short as a few nanoseconds have been shown to be suitable for wire marking. There is little information on the use of ultra short pulse lasers, i.e. < 1ns pulse duration. While theory suggests there is unlikely to be a lower cut off, this point is again somewhat academic.

3. Applied Laser Fluence: Typically ~ 1J cm^{-2}

The laser fluence applied to the wire is measured in Joules per square centimeter; i.e. it defines the energy density of a single pulse of the laser beam at the surface of the wire.

This is another key parameter. Below a threshold of about 0.1 J cm^{-2} no marking occurs, from 0.1 up to about 1 J cm^{-2} the contrast, or darkness of the mark, increases to a maximum, at which point it saturates. The exact contrast level and fluence at saturation is material dependent and no improvement will be gained by using higher fluence settings. There is obviously no practical advantage of operating above 1 J cm^{-2}.

To summarize, generally any pulsed UV laser with the following characteristics can be used and will produce a similar quality mark on aerospace wire:

Wavelength	200 - 380nm
Pulse length	< 35ns
Applied fluence	~1 J cm^{-2}

Provided a laser meets the above requirements, the actual choice of which laser to use within a wire marking system is primarily dependent on the operational requirement.

The key parameter of interest in terms of operational needs is the laser pulse repetition rate, quoted in Hertz (Hz). This gives an indication of the number of times per second the laser can be pulsed. This determines the print rate and must be matched to the operational requirement for the system's wire processing throughput or capacity. It will also define the average power of the laser.

Ultraviolet Lasers

Figure 1 shows a generic laser. Power is input to the active medium and then extracted as a laser 'beam' as light is emitted by the medium. The beam being created by light which is reflected back and forth and amplified between the lasers mirrors, before exiting through the partially reflecting / transmitting output mirror. Essentially, the laser is acting as an energy conversion device.

There are literally dozens of different types of ultraviolet lasers. They come in many shapes and forms. Wavelengths span the whole UV range; they may be continuous or pulsed and they utilise a variety of 'active laser media'; i.e. use different materials to convert the electrical power input to the laser to the output laser beam. These materials may be, in general, solid, liquid or gas.

Initial research showed that a variety of lasers could be used that met the general process requirements noted for wire marking. The actual choice of lasers is, however, limited by operational requirements.

The initial requirement was for a UV laser with relatively high average power, to support high speed operation for manufacturing. This limited choice to essentially one laser type - the excimer laser. As an off the shelf unit, this is still today the most convenient, efficient high power UV laser available.

Later requirements, for lower speed maintenance equipment have relaxed the average power demanded, thereby allowing consideration and utilisation of lower power solid state laser systems.

UV Excimer gas lasers

This class of laser uses a mixture of somewhat exotic gases, contained within a tubular pressure vessel, as the active medium. Power is input via a high power electric discharge between two long thin parallel electrodes situated in the gas mix and typically separated by about 25mm.

The resulting laser beam is rectangular and typically has dimensions of 25mm by 8mm, the larger dimension being defined by the electrode separation.

Different composition excimer gas mixes can be used to obtain different wavelengths. Those generally available are:

Gas	Wavelength
Krypton Fluoride, KrF	248nm
Xenon Chloride, XeCl	308nm
Xenon Fluoride, XeF	351nm

As can be seen, the wavelengths of all these excimer lasers fall directly within the UV range. The laser pulse lengths available from these lasers are dependent on the manufacturers detailed design and model type, but are typically in the range 12-35ns.

All of these lasers meet the general requirements for wire marking. The choice of laser is dictated only by practical considerations, in particular the maintenance and costs associated with use of the different excimer gas mixtures. To minimize these, the Xenon Chloride laser is used.

UV Solid State Lasers

There are no suitable solid state lasers which operate directly in the UV. However, by using the unique characteristics of high intensity laser beams, it is possible to generate ‘harmonics’ of a lasers ‘fundamental’ frequency (or wave length). These are true optical harmonics, exactly analogous to harmonic frequencies generated in other fields of technology, including electronics and acoustics. i.e. The harmonics are whole number multiples of the fundamental frequency.

It is important to note that a fundamental of a particular wavelength is effectively the same as and indistinguishable from a harmonic of a different fundamental, where both have the same wavelength. In the case of a laser this means that it is impossible to distinguish a beam from a laser which operates directly in the UV compared with a UV harmonic, of the same wavelength, generated from a laser with a higher wavelength fundamental output.

This process enables the use of lasers that would otherwise be incompatible with the noted wire marking requirements. In particular, the Neodymium YAG (Nd:YAG) laser has a fundamental output at a wavelength of 1060nm in the infrared. This laser has long been used in conjunction with harmonic generators, in the form of 'frequency multiplying' crystals, to create shorter wavelengths, as follows:

Primary frequency	Nd:YAG -	Fundamental =	1060nm
Frequency doubled	Nd:YAG -	1st harmonic =	1060/2 = 532nm
Frequency tripled	Nd:YAG -	2nd harmonic =	1060/3 = 355nm

The fact that the Nd:YAG laser generates multiple wavelengths, including an output in the infrared which is very clearly unsuitable for aerospace wire marking, may cause some confusion. However, in terms of its use for this application only the 355 nm wavelength is employed.

Figure 2 shows the optical arrangement to generate the UV frequency tripled output in a UV solid state Nd:YAG laser . The laser and the doubling and tripling crystals are physically mated to form a single device.

As with most situations the harmonic conversion efficiency, from the fundamental to the frequency doubled output and on to the frequency tripled output, is less than 100%. This means that there are some residual unconverted 1060nm and 532nm wavelengths within the laser beam after conversion to the UV. However, it is standard practice to design the optical system to transmit an essentially pure UV laser beam, while the unwanted wavelengths are directed in to a 'beam dump'.

Any residual unwanted wavelengths, which may be transmitted with the UV beam, are almost non-existent. Under normal circumstances the IR intensity is less than 1/100,000th (0.001%) of the UV beam. In a typical solid state UV laser wire marker this means that the average IR laser power is about 10 micro Watts, while the IR laser fluence is less than 10 $\mu J\ cm^{-2}$.

Conversion efficiency from the IR to the UV is dependent on 'tuning' of the crystals. Concerns that detuning would significantly increase the IR content of the transmitted beam can be allayed. Detuning effectively causes the harmonic UV beam intensity to decrease, but the IR beam intensity would increase, worst case, by a factor of 2, i.e. still totally negligible.

Conclusion

The required characteristics of pulsed UV lasers for use in UV laser wire marking systems for processing modern fluoropolymer aerospace wire constructions are clearly defined and well understood. At present, both UV excimer gas lasers and UV solid state frequency tripled Nd:YAG lasers can be used satisfactorily in such wire markers, subject to operational requirements which define the required laser pulse rates and average powers, which determine the wire markers capacity. There is no significant intrinsic difference between these lasers, in terms of marking process, provided that the UV solid state lasers are appropriately specified to ensure that any residue of the laser's fundamental infrared and green beams are suitably attenuated. In the case of CAPRIS wire marker's using solid state lasers, this is the case and the amount of infrared reaching the wire is infinitesimal, at less than 10μJ cm^{-2} fluence and 10μW average power; i.e. irrelevant.

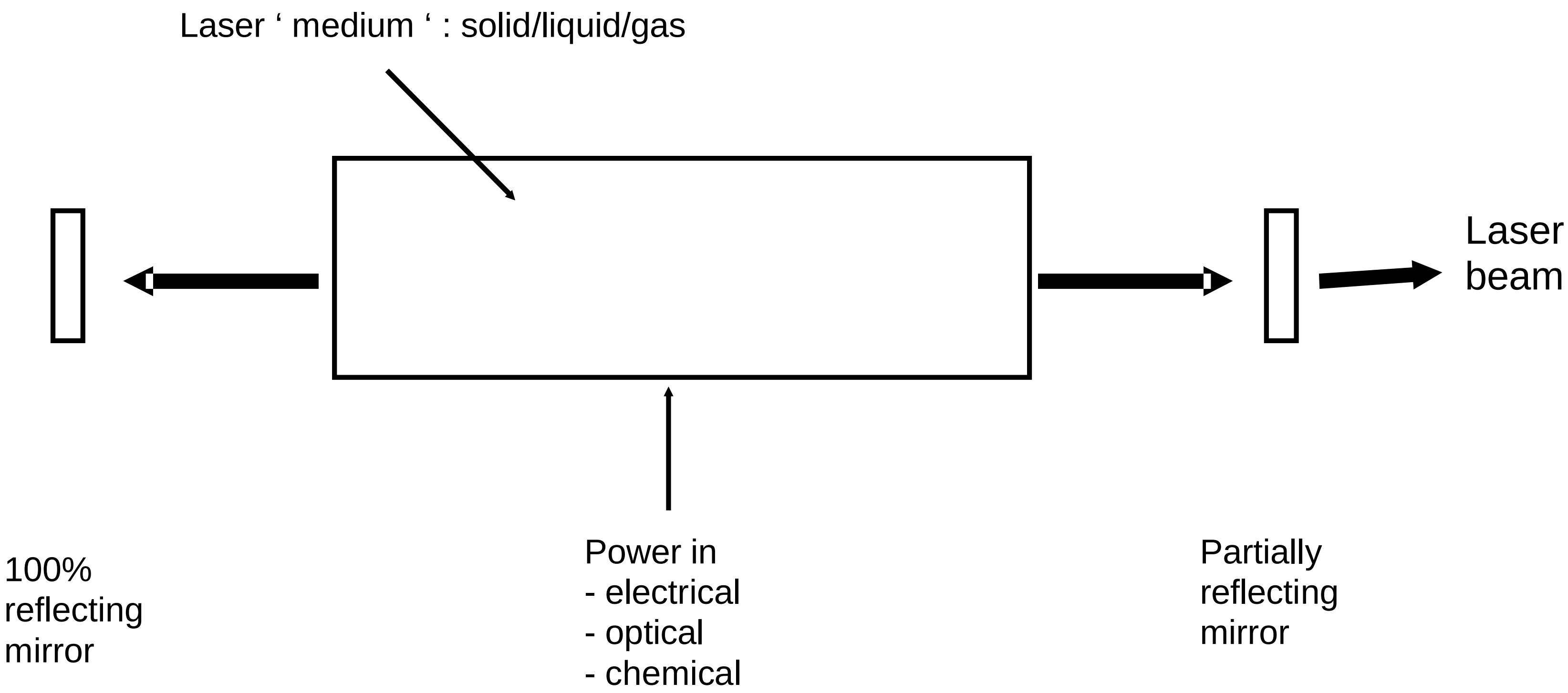
References

1. "Excimer Laser Printing of Aircraft cables", S. W, Williams, P. C. Morgan, ICALEO: International Congress on the Application of Lasers and Electro Optics; Oct 30 – Nov 4, 1988; Santa Clara, Ca.

FIGURE 1: THE LASER

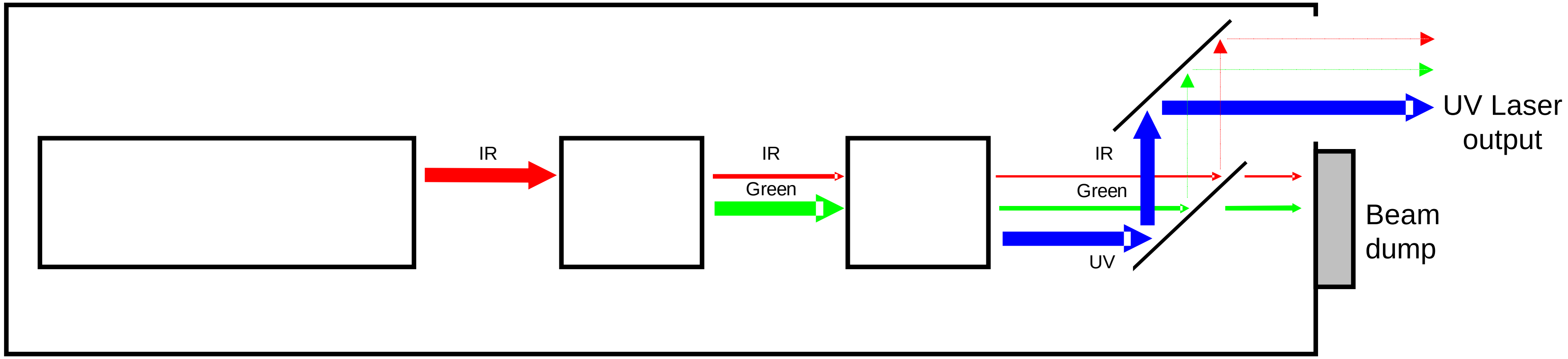
λ A device for converting power (normally electric) into a beam of ‘coherent’ high intensity light.

λ Light - electromagnetic radiation : Ultraviolet, visible, infrared (100nm to 10μm).



Harmonic generation : UV frequency tripled Nd:YAG laser.

Solid state UV laser



	Nd:YAG laser	Harmonic frequency doubling crystal	Harmonic frequency tripling crystal	Wavelength selective mirror
Wavelength nm	1064nm	532nm	355nm	
	Infrared IR	Visible	Ultra violet UV	

Applied laser fluence at wire

UV : 1 Jcm^{-2}

IR : $<10^{-5}$ Jcm^{-2}