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AEROSPACE INFORMATION REPORT

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Ultraviolet (UV) Lasers for Aerospace Wire Marking

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

1. SCOPE:

Ultraviolet (UV) laser marking for aerospace wire and cable is now a well established and accepted process. The purpose of this report is to provide general information on the technical basis of marking systems that apply UV laser energy to the wire surface. This includes materials for UV laser marking; the key characteristics of UV lasers suitable for this application, in terms of the mark process requirements and operational requirements; the various types of UV lasers which meet the general requirements for wire marking; and the generic components of UV laser marking systems. Subjects beyond the scope of this report include other wire marking systems not utilizing UV lasers; legibility; and contrast measurement.

2. REFERENCES:

[1] “Laser Beam Absorption and Mark Depth of Laser Marked Wires”, Philip Cornish et al., Report Ref: ST0012, Spectrum Technologies, December 9, 1997
[2] “User applied markings on wires: working towards perfect legibility”; Simon Lau and Claire Higgitt, AEISC conference paper October, 1997
[3] “Evaluation of excimer laser marked wires”; Paul Lefebvre, Canadian National Defence Quality Engineering Test Establishment; July 5, 1991
[4] “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.
[5] “Testing of MIL-W-22759 Wire Marked by (IR) Laser, Hot Stamp, Inkjet and Dot Matrix Methods”; Rex A. Beach, Naval Avionics Center Test Report TR-2436; June 30, 1989

2.1 Further Reading:

“Ultraviolet UV lasers for aerospace wire marking”; P.H. Dickinson, Spectrum Technologies plc report ST001, November 6, 1997

“Relationship between composite wiring markability and wet arc resistance performance”; Brad Elik, AEISC, Norfolk, VA, October 20, 1999

3. DEFINITIONS:

LASER: (Light Amplification by the Stimulated Emission of Radiation). A source of intense monochromatic light in the ultraviolet, visible or infrared region of the spectrum. Solids, liquids and gases may be used as the active or lasing materials. The laser beam is generated by ‘energizing’ the active medium by power from an external source. The power source is most commonly electrical or optical.

INFRARED (Abbreviation - IR): Electromagnetic radiation in a wavelength range from approximately 700 nm to in excess of 10,000 nm.

ULTRAVIOLET (Abbreviation - UV): Electromagnetic radiation in a wavelength range from approximately 200 to 400 nm.

3. (Continued):

IR LASER: a laser that produces a beam of radiation in the IR range.

UV LASER: a laser that produces a beam of radiation in the UV range.

FLUENCE: the energy density, measured in J cm^{-2} (Joules per square cm) of a single pulse of the laser beam at a surface, which, for the purposes of this document, is the wire insulation.

PULSE LENGTH: The time interval between the laser energy crossing half the maximum energy on the rising and the falling edge of the pulse. For the applications discussed here, pulse lengths are measured in nanoseconds, ns. 1 ns = 10^{-9} s

WAVELENGTH (λ): $\lambda = c/f$ where c is the velocity of light and f is the frequency. Wavelength is measured in nanometres, nm. 1 nm = 10^{-9} m.

DAMAGE: for the purposes of this document, damage is defined as an unacceptable reduction in a wire insulation's mechanical or electrical properties, i.e., a reduction outside of its defined specification.

Nd (NEODYMIUM): Neodymium is an elemental metal, which forms the active laser material in the most common type of solid state laser. The neodymium is held in an optically transparent solid 'host' material, and is energized by optical input, either from flashlamps or from the optical output of diode lasers. The host material does not play a direct role, but can slightly influence the laser wavelength. Typical host materials are specialised crystal materials, such as YAG and YLF (see below). These lasers are commonly referred to as Nd:YAG or Nd:YLF. The primary wavelength of Nd solid state lasers is in the infrared (IR) at a wavelength of approximately 1064 nm. The IR output of such lasers can be conveniently reduced to lower wavelengths by use of harmonic generation (see below).

YAG: Yttrium Aluminum Garnet, the crystalline host material most commonly used for Neodymium lasers.

YLF: Yttrium Lithium Fluoride, an alternative crystalline material used for Neodymium lasers.

EXCIMER: a gas laser deriving its name from the term "excited dimer". The laser is energized by means of a gas discharge. Excimer lasers are available operating at a number of discreet wavelengths throughout the UV, the most common of which are 193, 248, 308, and 351 nm. The wavelength is purely dependant on the gas mix used.

HARMONIC GENERATION: the use of non-linear processes to frequency multiply the output of a high intensity laser beam. This enables the wavelength of an infrared laser to be converted to the green and/or the UV.

4. ULTRAVIOLET (UV) LASER WIRE MARKING:

4.1 Materials for UV Laser Marking:

Ultraviolet (UV) laser marking is compatible with fluoropolymer insulations including polytetrafluoroethylene (PTFE); ethylene tetrafluoroethylene copolymer (ETFE); fluorinated ethylene propylene (FEP). Wire insulation types suitable for UV laser marking are tabulated below, however, this list is not exhaustive and UV laser marking may also be applied to other polymeric insulation materials

The UV laser beam causes a color change in the insulation material, creating a permanent mark without affecting the insulating properties of the wire or cable. The UV laser mark appears gray/ black in color on light colored insulations, particularly those pigmented with TiO_2 (titanium dioxide). TiO_2 is used in wire insulation materials as a white pigment and/or opacifying agent, though it is not the only pigment available.

NOTE: UV laser wire markers should not be used for marking aerospace wires for which they have not been specified without establishing the suitability of the wire marker to process such wires. It is inappropriate to process top-coated aromatic polyimide insulated wires with this type of equipment, such wires will not mark with UV lasers.

TABLE 1

Insulation type	Comments
Polyimide/PTFE or FEP topcoat	Fluoropolymer top-coated polyimide wires with very good laser markability have been available for some time. Recent improvements have further increased the mark contrast achievable on both FEP and PTFE topcoats to 65-70%.
Polyimide/PTFE tape	UV laser markable composite PTFE/polyimide wire constructions are widely used. Good mark contrasts, of 58-70%, are achievable on current UV laser markable stock.
ETFE, XL-ETFE extrusion	ETFE is frequently used as a wire insulation either in its natural state or cross-linked (XL-ETFE) for improved physical properties. In general, modern ETFE and XL-ETFE wires, where the pigments, color formers and processes are carefully controlled, give high contrast results (>70%).
PTFE extrusion	This wire construction, less frequently used in aerospace wiring, may be UV laser marked. These wires have not yet been specified to the same high standard for laser markability as, for example, ETFE extrusions. Mark contrasts of around 50% are achievable on standard product through testing and selection.
FEP extrusion	Extruded FEP wire and cable is less widely used, but can be UV laser marked, 70% contrast having been achieved on this wire type.

4.2 Properties of UV Laser Marked Materials:

UV laser marked PTFE/polyimide wire forms a uniform gray coloration which is shallow compared to the thickness of the outer insulation (Figures 1 and 2). The UV laser mark on XL-ETFE wire is composed of two layers, an outer darker area, and an inner, lighter area (Figures 3 and 4). On some ETFE insulations the mark may appear brown/black. Both the appearance of the marks and the mark depth produced by both excimer and solid state UV laser systems are very similar for each wire type [1].

TABLE 2 - UV Laser Mark Depths on Aerospace Wire Insulation

Insulation type	Mark Depth
XL-ETFE	18.5±1μm
PTFE/polyimide	8.5±1μm

The mark process operates by a change of color of the wire insulation and not by burning, impacting or removal of the wire insulation.

UV laser marking has been the subject of extensive testing, from which it has been established that there are no known effects on the electrical or mechanical properties of the wire insulation. Further details are available in references [2] and [3].

5. UV LASER PARAMETERS FOR WIRE MARKING:

The initial discovery and development of UV laser wire marking was carried out and reported on by British Aerospace in 1987/1988 [4]. During this initial work a variety of UV lasers were investigated for their effectiveness in marking aerospace wires. These include lasers operating at 248, 308, and 351 nm. The net result of these investigations defined the general requirements for UV laser marking.

The laser characteristics can be grouped under

- Process Requirements, i.e., those characteristics which affect the marking process in terms of the mark characteristics and quality, and
- System Requirements, i.e., those characteristics which affect the performance of equipment in terms of its operational use.

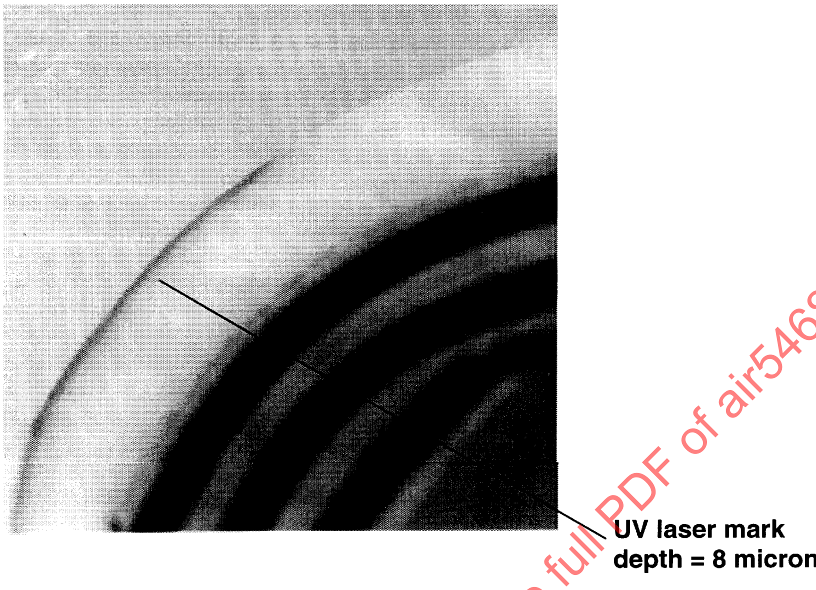

FIGURE 1 - Optical Micrograph of Cross-Sectioned PTFE/Polyimide Wire Marked With Frequency Tripled Nd-YAG Solid State UV Laser

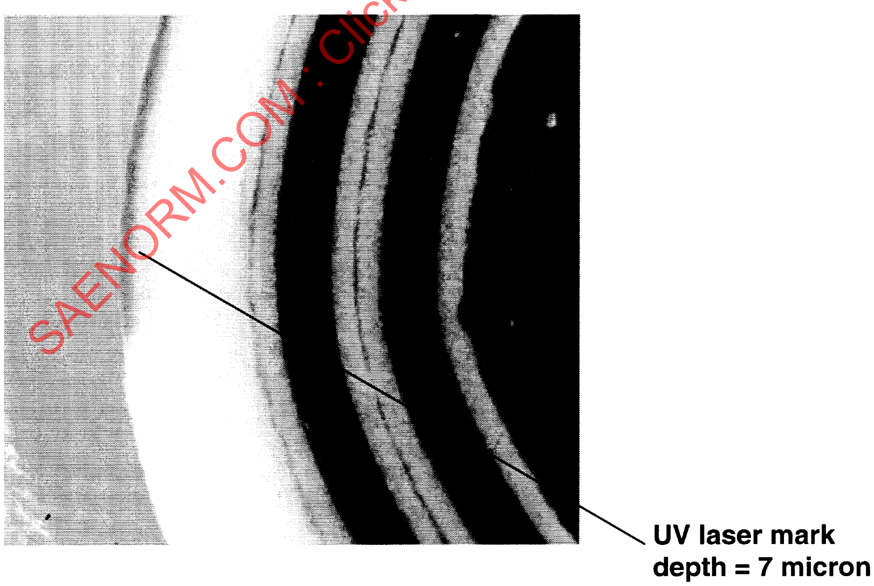

FIGURE 2 - Optical Micrograph of Cross-Sectioned PTFE/Polyimide Wire Marked With XeCl Excimer UV Laser

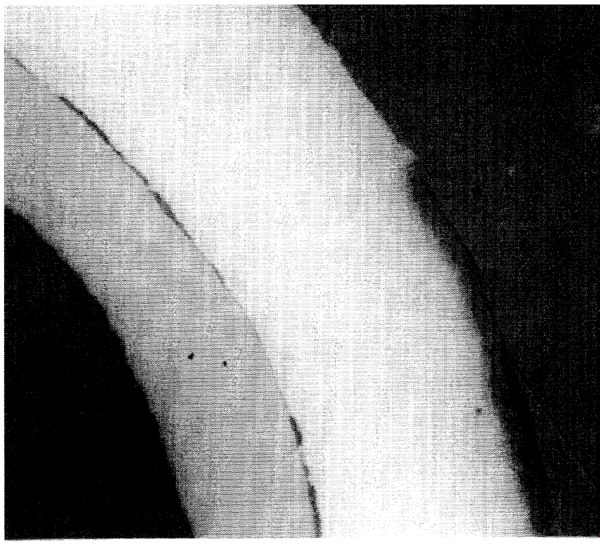

FIGURE 3 - Optical Micrograph of Cross-Sectioned XL-ETFE Wire Marked With Frequency Tripled Nd-YAG Solid State UV Laser

FIGURE 4 - Optical Micrograph of Cross-Sectioned XL-ETFE Wire Marked With XeCl Excimer UV Laser

5.1 Process Requirements:

5.1.1 Laser Wavelength: Typically 200 to 380 nm (1 nm = 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.

The wavelength range spans the UV from the deep ultraviolet, ~ 200 nm, to the near visible, 380 nm. Lasers with wavelengths in the range 193 to 355 nm 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 this region was found to be effective.

The lasers and wavelengths most commonly employed are the xenon chloride excimer laser with a wavelength of 308 nm, and the Neodymium:YAG and Neodymium:YLF frequency tripled lasers with wavelengths in the band of 353 to 355 nm. The latter should not be confused with Neodymium:YAG and Neodymium:YLF lasers without frequency tripling and which have an output in the infrared (IR).

WARNING: Long wavelength infrared (IR) lasers are not suited to marking fluoropolymer aerospace wires as the laser beam makes an intrusive mark and can cause damage to the wire insulation.

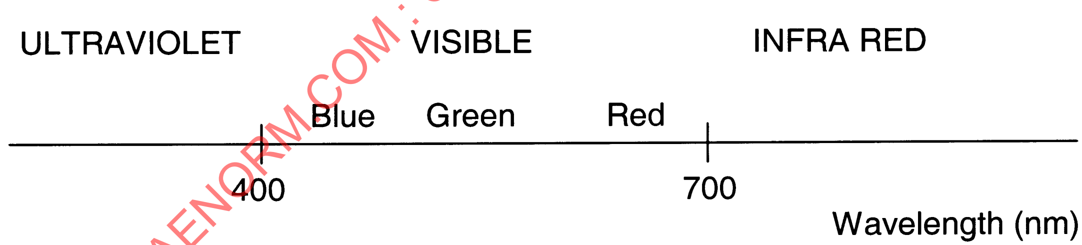

FIGURE 5 - Electromagnetic Spectrum of Visible and Invisible Light

5.1.2 Laser Pulse Length:

Typically <35 ns (1 ns = 10^{-9} s)

The laser pulse length is a critical parameter in achieving the desired marking process. It has been found necessary to use short pulse lasers to generate a good mark. Lasers with pulse lengths between 3 and 35 ns have generally been found to be suitable. The actual upper limit has not been firmly established at this time due to the lack of suitable lasers with pulse lengths in the range 35 to 1000 ns. There is no information on the use of ultra short pulse lasers of <1 ns pulse duration. However, theory suggests there is unlikely to be a lower cut off.

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 and may cause damage to the wire insulation.

5.1.3 Applied Laser Fluence:

Typically ~ 1 Jcm^{-2}

The laser fluence applied to the wire is measured in Joules per square centimeter. This is another key parameter. Below a threshold of about 0.1 Jcm^{-2} no marking occurs. From 0.1 up to about 1 Jcm^{-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.

5.1.4 Summary of Process Requirements: 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 to 380 nm
Pulse length: < 35 ns
Applied fluence: ~1 Jcm^{-2}

5.2 System Requirements:

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

The laser pulse repetition rate, quoted in Hertz, indicates how many times per second the laser can be pulsed. The average power of the laser is the product of the repetition rate and the energy per pulse delivered by the laser for marking the wire. In the case of mask based imaging systems printing one character per pulse, repetition rates are typically in the range of 10 to 200 Hz at pulse energies in the range 50 to 200 mJ. In the case of vector marking systems, repetition rates are typically in the range 1 to 10 kHz at pulse energies of 0.3 to 0.6 mJ.

5.3 Future Developments:

Readers should be aware that the information provided is based upon the current state of knowledge and that future research may result in changes to the above guidelines. This may result in new derivatives of UV laser wire marking systems, which operate with parameters outside these guidelines. In such cases users must satisfy themselves that the new systems are entirely suitable for the intended application.

6. ULTRAVIOLET LASERS:

6.1 Laser Technology:

Figure 6 shows a generic laser. Power is input to the laser ‘medium’ and then extracted as a laser ‘beam’ as light is emitted by the medium. The beam is created by light which is reflected back and forth between the laser mirrors and amplified as it passes through the energized laser medium, before exiting through the partially reflecting/transmitting ‘output’ mirror. Essentially, the laser is acting as an energy conversion device.

6.2 Ultraviolet (UV) Lasers for Wire Marking:

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 utilize 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 which met the general process requirements noted for wire marking. The actual choice of laser is, however, limited by operational requirements.

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

Subsequently, requirements for lower speed wire marking equipment to support maintenance operations, along with the development of industrial rated solid state lasers with harmonic generating systems for frequency tripling, have led to the use of lower power solid state UV lasers in wire marking systems.

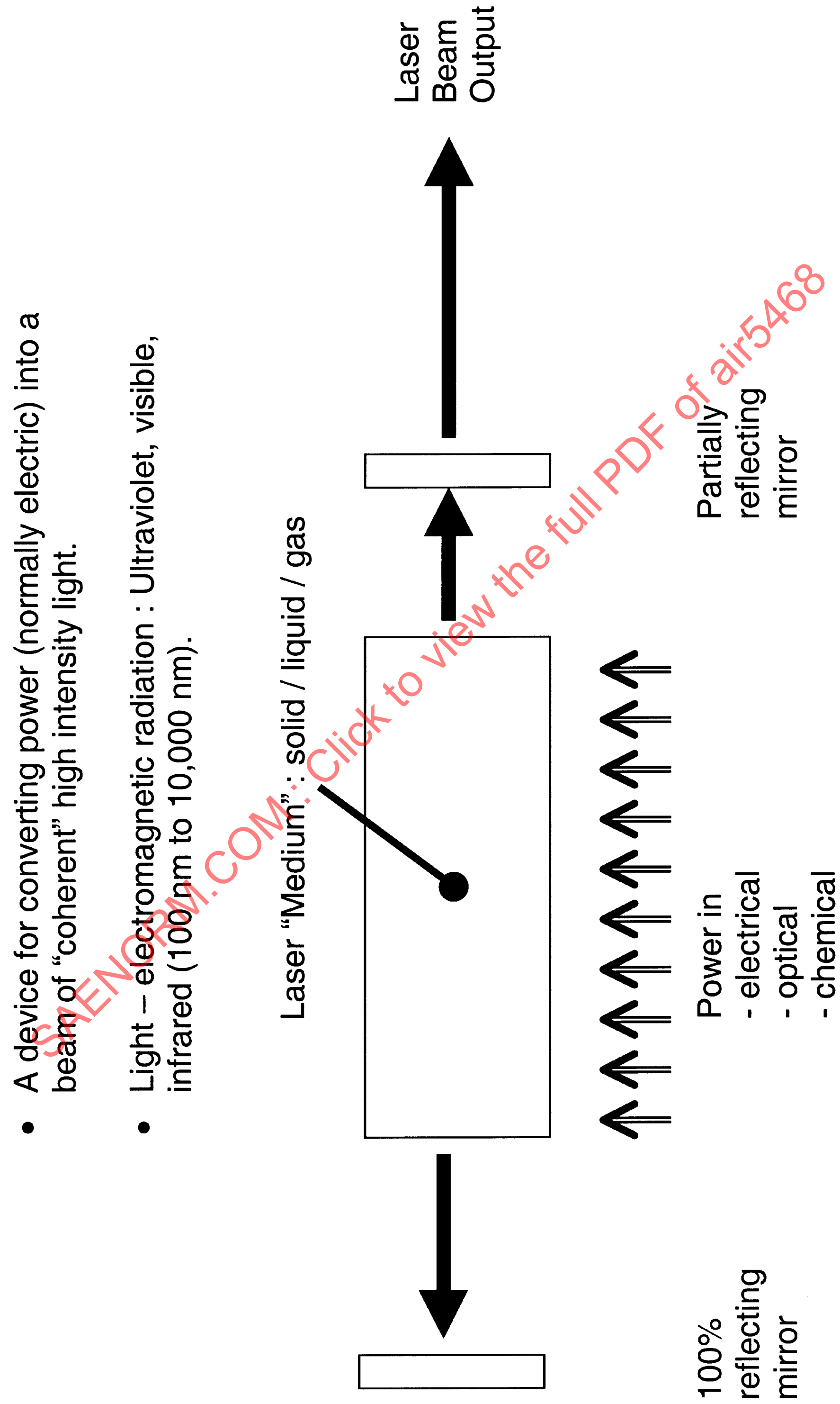

FIGURE 6 - The Laser

6.2.1 UV Excimer Gas Lasers: This class of laser uses a mixture of special 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 25 mm. The resulting laser beam is rectangular and typically has dimensions of 25 mm by 8 mm. 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:

a. Krypton Fluoride, KrF, 248 nm
b. Xenon Chloride, XeCl, 308 nm
c. Xenon Fluoride, XeF, 351 nm

The wavelengths of all these excimer lasers fall directly within the UV range. The laser pulse lengths available from these lasers are dependant on the manufacturer's detailed design and model type, but are typically in the range 12 to 35 ns.

All of these lasers meet the general process requirements for wire marking. The choice of laser is dictated only by operational 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.

6.2.2 UV Solid State Lasers: There are no suitable solid state lasers that operate directly in the UV. However, by using the unique characteristics of high intensity laser beams, it is possible to generate 'harmonics' of a laser's 'fundamental' frequency (or wave length). These are true optical harmonics, 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, on the basis of wavelength alone, 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.

As an example the Neodymium YAG (Nd:YAG) laser has a fundamental output at a wavelength of 1064 nm 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 = 1064 nm
Frequency doubled Nd: YAG - 1st harmonic = 1064/2 = 532 nm
Frequency tripled Nd: YAG - 2nd harmonic = 1064/3 = 355 nm

6.2.2 (Continued):

The Nd:YLF laser provides a near identical range of wavelengths.

The fact that these lasers generate multiple wavelengths, including an output in the infrared, which is very clearly unsuitable for modern aerospace wire marking [5] may cause some confusion. However, in terms of their use for this application only the third harmonic in the UV should be employed.

Figure 7 shows in simplified form the optical arrangements to generate the UV frequency tripled output in a UV solid state laser, while removing the visible and IR residual wavelengths using a wavelength selective optical component.

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 IR and visible wavelengths within the laser beam after conversion to the UV. However, the optical systems used remove virtually all the unwanted wavelengths while transmitting an essentially pure UV laser beam. The unwanted wavelengths are directed into a 'beam dump'.

Any residual unwanted wavelengths that may be transmitted with the UV beam should be of a very low power. 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 at the wire is less than 10 µJ cm^{-2}. These values are quite acceptable.

Conversion efficiency from the IR to the UV is dependent on 'tuning' of the crystals. Should detuning occur, this would cause the harmonic UV beam intensity to decrease, but due to the design of these systems the IR beam intensity should increase, worst case, typically by a factor of two, i.e., still totally negligible.

In the event of optical misalignment or damage to optical components, the system design should be such that no significant IR may reach the wire. There should therefore be no requirement for any detection/warning system unless the system design does not preclude or minimize the possibility of IR radiation reaching the wire to reasonable limits.

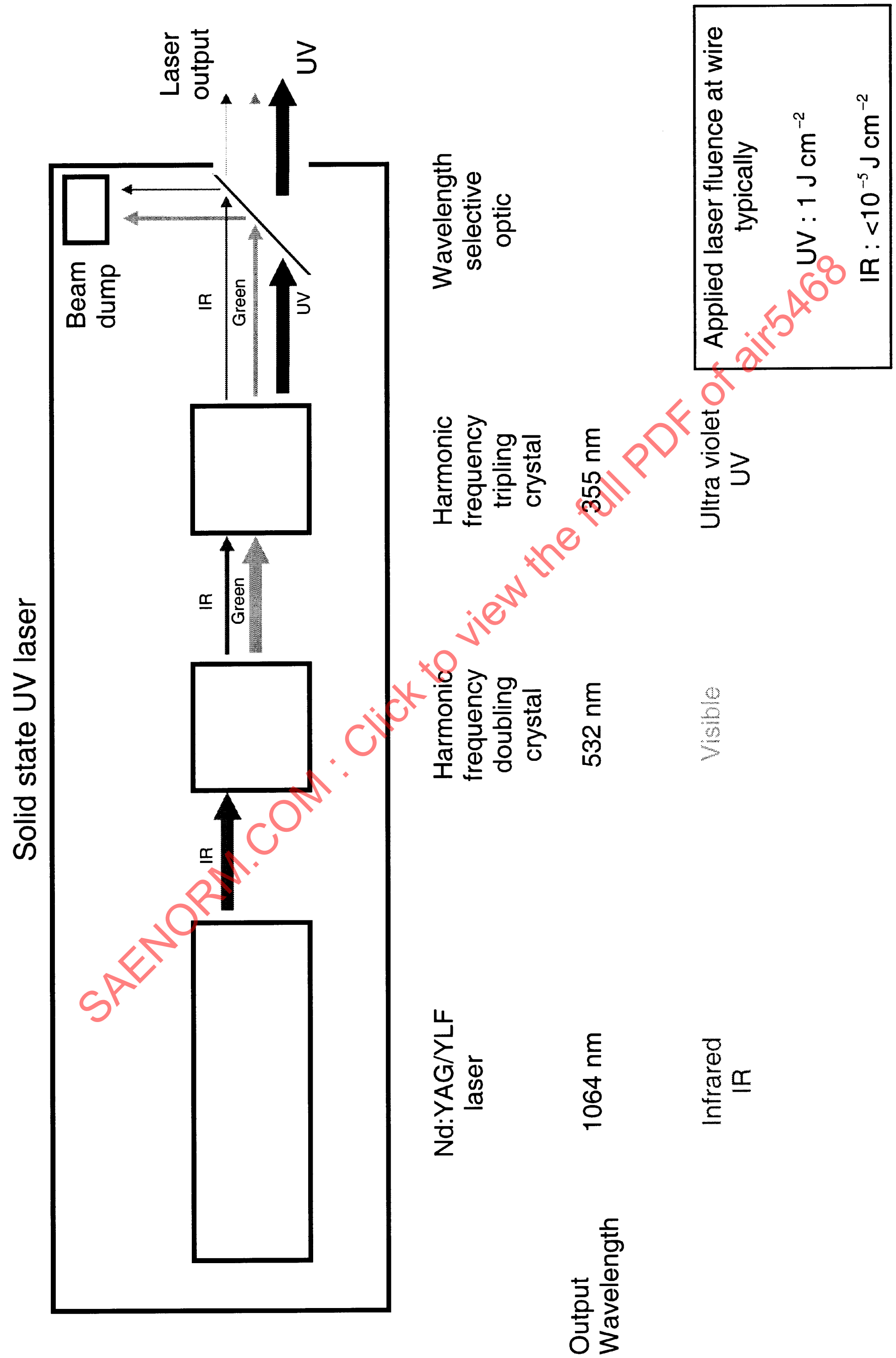

FIGURE 7 - Harmonic Generation : UV Frequency Tripled Nd Laser