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A TECHNOLOGY FOR TRACEABLE, QR-CODED SECURITY FOR PRECIOUS GEMS

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INTRODUCTION

Seculuxe

Over the last five or six years the research department at Diamond Centre Wales (DCW) have been working with photonics department at Bangor university in Wales to design and develop a technology capable of safely and securely laser marking a very small QR code on to the table or internal structure of precious gemstones, particularly diamonds. This research has now become a viable proposition resulting in two demonstrator laser marking machines undergoing proof of concept trials at DCW early in 2025. To achieve this breakthrough three distinctly different, but closely aligned, laser-based technologies had to be developed and refined into a single cohesive and practical output which in simple terms could be described as "we developed a laser marker, it makes very small marks, and we can read and make use of those marks." However, this would be a gross, but certainly accurate, oversimplification and this paper aims to explain the research and the results of that research in both simple, layman's terms whilst also offering those who might wish to explore further the more detailed science, results and methodologies of the research, and in order to achieve this we have divided the paper in to two distinct parts.

Part one will be the simple less technically explicit and ‘light’ on the science version.

Part two will be as much of the ‘heavy’ science as required for those who might wish to delve further into the detailed theories and workings that went into the research for the project. A research project that was named The Seculuxe Project which is meant to indicate ‘security for luxury products’

PART 1: THE LIGHT SCIENCE

At the 2024 Jewelry Symposium we presented information and data about the Tui-Tech project, a technological development to automatically and quickly identify the quality and brilliance of precious gemstones, particularly diamonds. In the conclusions of the paper and presentation we also identified a worrying new trend of counterfeit laser marks indicating the gemstones quality being identified (in that particular case study by the Grading Lab of The Gemmological Association of America) on the girdles of supposedly natural diamonds. It is clear from this and other reports that the laser marking technology typically used to mark and identify high value diamonds, and other gemstones, is now easily accessible to any unscrupulous gemstone dealer around the globe.

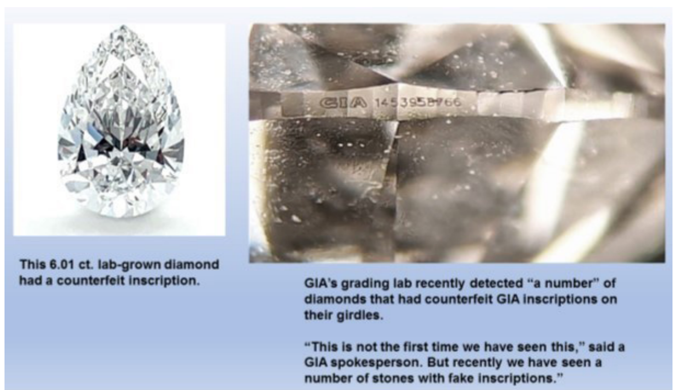

Figure 1: Slide from the 2024 Jewelry Symposium presentation

A Short Laser Technology 101

In the American educational system, “101” indicates an introductory course, often with no prerequisites. The meaning has been extended to include any introduction to the basics of anything.

Why is it called a Laser? The term stands for “Light Amplification by Stimulated Emission of Radiation.” There are many different types of lasers, almost as many as there are applications for the lasers but what links them together as a distinct technology is that they depend on the same photonic effect: stimulated emission. In this particular case, the emission of light.

Lasers exploit particle physics to convert electrical power into a very tightly concentrated beam of light.

Lasers require a source of energy, typically an electrical current, a gain medium,[1] a feedback mechanism,[2] and an output beam (the actual Laser Beam).

Adding energy to a particle causes it to enter an excited state, from which it wants to return to its lower-energy norm in accordance with the laws of thermodynamics.[3] In this case, the energy is electromagnetic, so our particle is an electron. Lasers normally use electrical power to add energy to the gain medium which is a substance that can engage in stimulated emissions. The gain medium can be a solid, liquid, or gas. To drop back to its original energy level, the “stimulated” electron must release the energy it has absorbed, which is emitted as a photon: probably best described as a single packet of light.

Physicist Anita Chandran, explained it well with emojis:

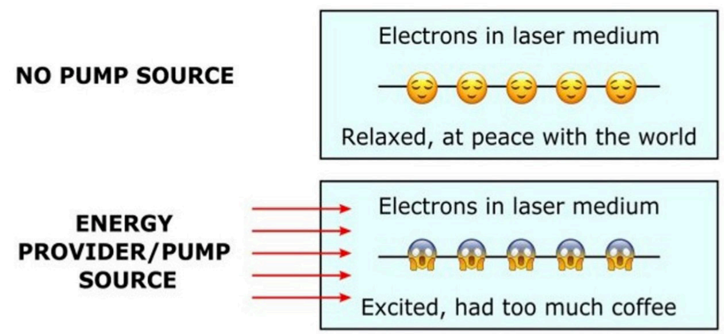

Figure 2: ‘Relaxed’ and ‘Stimulated’ electrons

Once more than half of the gain medium has absorbed enough energy to be in a higher-energy state, an optical feedback process begins, not unlike the ear-splitting shriek of audio feedback created if you get a microphone too close to its speaker. Photons released by the gain medium reach a critical density and start exciting the medium themselves, and the whole sample starts emitting light that becomes lined up on every level: the photons have the same frequency and polarization, and they're perfectly in phase. This Nirvana-like state of alignment is called coherence. Again, illustrated here by Anita Chandran:

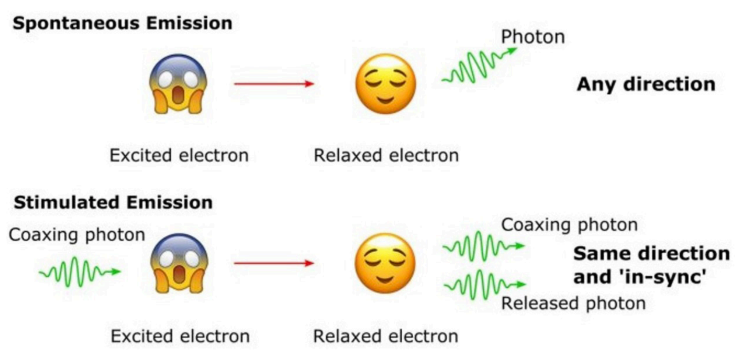

Figure 3: Photon emissions

The direction in which any given photon goes when it's emitted is typically random, which is why light radiates outward from a source in all directions. However, photons emitted by the gain medium stay bouncing around within it, trapped by the reflective walls of the reaction chamber. The physical shape of the chamber, usually cylindrical, constrains the path any photon can take, gathering all possible exit paths from a sphere into a narrow, collimated output beam. In contrast to an ordinary light source, a laser produces a narrow beam of very bright light, laser light is "coherent," which means that all a laser's light rays have the same wavelength and are in sync.

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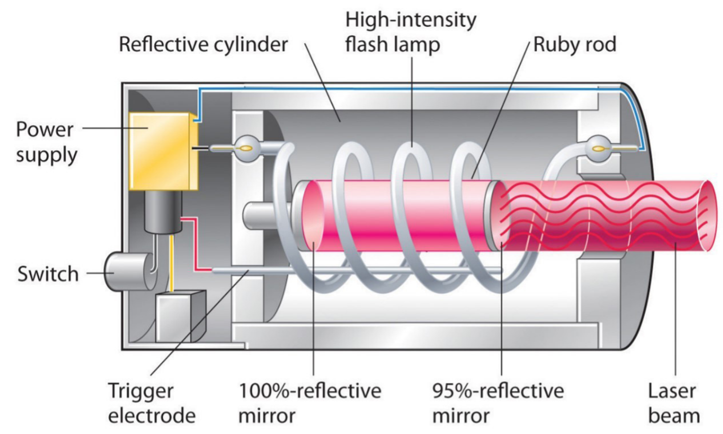

Figure 4: Simplified Laser Schematic

Focusing a Laser Beam Through a Single Lens
A laser beam is normally focused through a single focal lens. The focal lens acts like a magnifying glass under sunlight and focuses the random light rays down to a single spot. For a 55mm lens, the laser beam passes through the lens and converges to the smallest point at about 55mm from the lens. The laser beam is concentrated to its smallest size at this "spot".

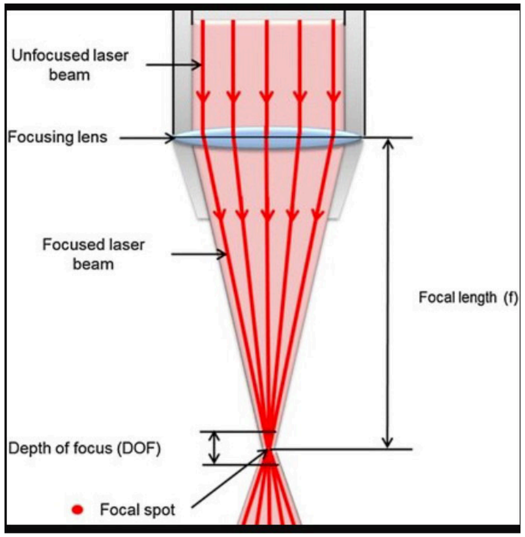

Figure 5: Single lens focusing

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Two Lens Focusing
An essential element of the research for the project was to develop a suitable lens configuration that enabled the clear and concise focusing of the laser beam such that it was able to mark at a nano scale yet still produce a readable QR code onto the surface (or internally) of the diamond without damaging or affecting the integrity of the diamond and so adversely affecting the intrinsic value of the diamond. To achieve this and based on existing research undertaken by the Photonics lab at Bangor university,[4] a Plano-Convex Microsphere (PCM) lens was developed. The effectiveness of this lens configuration was further enhanced by undertaking additional research into the power, scanning speed and frequency of the laser beam being used to mark the diamond.

A PCM lens is simply a tiny, fifty-micron diameter, glass bead, the microsphere, encapsulated to the larger single focus lens, for the early research on this project the encapsulation was done using superglue! A more detailed view of the PCM lens and manufacturing process can found in Figure 16.

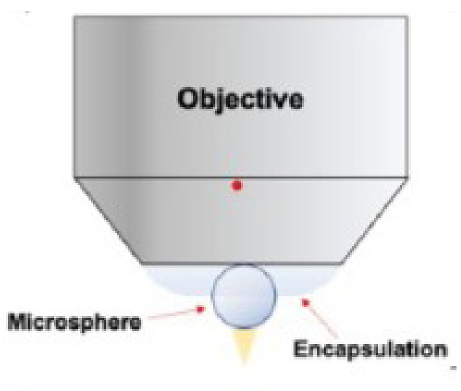

Figure 6: A Plano-convex lens

QR Code Reader/Scanning Tool
Having developed the technology to place micrometre scale QR codes on the surface of gemstones, using the power of the finely focused laser beam described, a methodology and technology was developed to facilitate the reading and digital machine reading of the QR code. The micro-scale of the code prevents it disrupting the aesthetics of the stone, as it is smaller than the eye can see, and the machine-readable nature of a QR code means that there is no need for specialised training in order to read it along with the removal of the possibility for human error in any ongoing data entry that may be required. It should also be a significantly faster process. The caveat here is that as the code is micro-scale, a device, system or process needed to be developed that will allow an untrained individual to find and read the QR code. More detailed information and images of the various scanner options are available below.

The final phase of the project was to introduce the coding necessary for the blockchain elements The QR code, which is unique to each marked gemstone or diamond, is linked to a secure database to generate a completely traceable solution giving a full product lifecycle and distribution ledger that cannot be altered or tampered with. Blockchain technology, as applied in this project, deserves its own dedicated paper and fortunately this has already been done by Santa Fe Symposium® alumni and speaker at the 2025 The Jewelry Symposium Anne B. Miller, in her paper titled *Blockchain: Stories from the Field*, from 2022.[5]

PART 2: THE HEAVY SCIENCE
Several research papers and collaborations between Diamond Centre Wales and The Photonics Department of Bangor University were the grounding for the science used in developing the Seculuxe technology and are summarized below.

The Seculuxe laser technology is based on an innovative low power laser system with the ability to mark a QR code on a nano[6] scale (1 nanometre = 0.000000001 m), the marking system is paired with a secure digitised ledger which will offer authenticated blockchain security. A low-cost identification scanner to read the marks has also been developed in conjunction with the marking technology. The system can achieve a much higher fidelity (the degree of exactness with which something is copied or reproduced) QR code at a much smaller scale than currently achievable using the aforementioned more 'traditional' laser marking technologies. This is achieved by the inclusion of an innovative 'super-lens' technology developed in partnership with Bangor University in the UK at their Centre of Photonics expertise (CPE)[7] in Wales. Once the nano code has been engraved on to a gemstone it has no detrimental effect on its integrity or condition, and therefore value, due to the extremely high fidelity and precision of the mark/QR code. Making this process the ideal solution to give security and traceability to any gemstone where the traditional marking solution is easily viewed, removed, altered or added.

The technology achieves the laser engraved QR codes with features as small as 350 nm, well below the typical 800 nm laser wavelength. This nano-laser marking technology has a super lens design called a PCM (Plano-convex microsphere lens). This consists of a standard plano-convex lens and glass microsphere with a 50-micron diameter that is encapsulated to the lens. This super lens enables large area complex designs to be made with improved reliability and repeatability compared with other currently known microsphere-based laser fabrication technologies. The design and working of a novel two-lens focusing system allows the technology to inscribe diamonds at microscale and at a high throughput rate using an ultrafast laser scanning process. A threshold laser fluence (the ablation threshold is a useful tool for measuring the effectiveness of a technique at etching a material: low threshold fluence indicates that minimal laser energy is required to remove material from a substrate) of 2-3 Joules per square centimetre and a scan speed of 2 mm per second enabling writing of a high-contrast data matrix code and serial number without inducing defects and cracking in the diamond. Although, several conventional technologies are available for surface marking and inscribing of industrial products, marking by lasers is unique in the sense it is quick, more reliable and automated. Therefore, many industries and businesses have been adopting these for scribing serial marking on gemstones in a user-friendly and viable process without influencing their surface quality. Nanosecond pulsed lasers, such as excimer lasers (wavelength 193-355 nm), have demonstrated success to ablate and mark a variety of optically transparent materials due to their greater absorption coefficient.

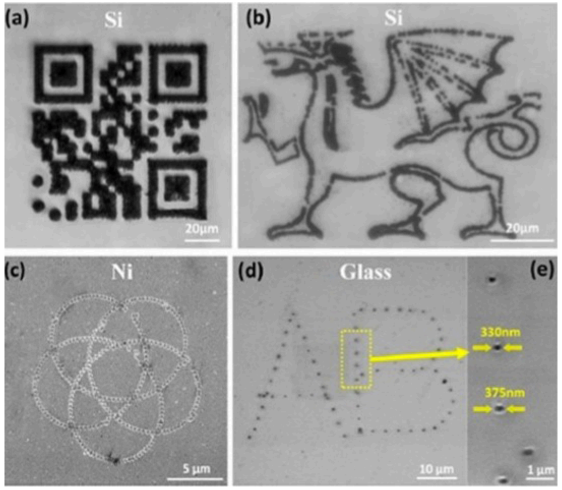

Figure 7: Early arbitrary marking tests on various substrates— On a silicon wafer: (a) Bangor University website QR code, (b) The Welsh Dragon. On a nickel substrate: (c) Guilloche pattern on a glass substrate, (d) letters, (e) enlarged image of highlighted area in (d)

Short, pulsed lasers are typically used for the marking of transparent materials, this projects challenge was to produce digital security micro-features on facets of a natural diamond in a non-intrusive and non-destructive manner. We developed a novel two-lens focusing system able to inscribe a diamond at microscale and with a potentially high throughput by using an ultrafast laser scanning process. A threshold laser fluence of 2-3 J/cm2 and a scan speed of 2 mm/s realized the creation of a high-contrast data matrix code and serial number without inducing defects or cracking in the diamond. Comparison and Characterization revealed a smooth ablation depth profile with distinct Laser-Induced Periodic Surface Structures (LIPSS)[8] in the laser inscribed regions. This was determined through scanning electron microscopy (SEM) and 3D optical microscopy in the Bangor University CPE. Further Raman spectroscopy revealed a diamond cubic structure dominating with mixing of graphitic structure in the laser markings at various scanning speeds. When compared with the typical 0.05 NA f-theta lens,[9] the two-lens focusing system developed offered a factor of seven times improvement in the marking resolution (3 µm in linewidth) in addition to its simplicity and add-on flexibility when compared to traditional industrial laser marking systems currently used for marking gemstones.

Although, several conventional technologies are available for surface marking and inscribing of industrial products, marking by lasers is considered unique in the sense it is quick, more reliable and easily automated. Therefore, many industries and businesses have been adopting these for scribing serial marking on gemstones in a user-friendly and viable process without influencing their surface quality. Nanosecond (ns) pulsed lasers, such as excimer lasers (wavelength 193-355 nm),[10] have demonstrated success to ablate and mark a variety of optically transparent materials due to their greater absorption coefficient. However, material processing by these ns-lasers is accompanied by low ablation rate and induced photo-thermal effects which challenge the desired high-resolution and defect-free microscale marking of diamonds.

Due to their shorter pulse duration and higher peak power compared to ns-lasers, ultrafast lasers enable cold processing (interaction times are shorter than the electron/photon coupling time) leading to the enhanced micromachining quality of a wide range of industrial materials. Meanwhile, work in the field of Femtosecond (fs) (one femtosecond is 10ˆ-15 seconds, or a quadrillionth of a second). A femtosecond laser is a type of laser that emits extremely short pulses of light, with each pulse lasting on the order of femtoseconds These lasers can produce incredibly precise and high-energy pulses of light, making them ideal for a wide range of scientific and industrial applications. Laser based micro-processing of natural diamonds and gems has been growing due to global concern for safe keeping as well as fast-track traceability through digital marking. First reported on fs-laser writing of linear patterns at different powers and focal depths inside the natural bulk diamond at the pulse repetition rate of 10 Hz.[11] Recently, Gomes et al. demonstrated the ultrafast laser inscription of QR-codes on diamond, ruby and sapphire.[12] A low repetition rate fs laser (1 kHz) was used to inscribe QR-code consisting of microdots on the natural diamond to overcome defect clusters and graphitization.[13] Table 1 lists the results obtained from previous reports and compares the laser processing parameters adopted for various types of diamonds.

Table 1: Table of laser processing parameters

Table 1
Reported experimental results on ultrafast fs-laser (700-800nm, 100-120fs) processing of diamonds

Pulse energy (μJ)	Freq. (Hz)	Laser intensity (J/cm^2)	f-spot size (μm)	Marking size (μm)	Obj. NA	Diamond type	Ref.
9-100	10	-	10-30	120-240	0.17, 0.4	SCD (n)[a]	[11]
4	1000	2.34	14	432×432	0.17	SCD (n)	[12]
400	-	0.3-0.4	3	-	-	SCD (s)[b], SCD (n)	[13]
0.1-1.3	1000	-	2-5	6-13	1.4	SCD (s)	[14]
8-12	5000	2.23-3.82, 169	20, 3	100×150, 20×25	0.05, 0.6	SCD (n)	this paper

[a]Single crystal diamond (natural); [b]Single crystal diamond (synthetic)

We report here on a new fs-laser scanning process by writing alphanumeric labels and identifiable security code on the polished facet of the natural diamond (derived from standard gem cutting and polishing) in ambient conditions. A design for focused laser scanning has been applied and marking of serial number and data matrix code, 25-100 μm in height, is successfully demonstrated. The add-on 0.60 NA focusing objective led to a 7-fold improvement in the marking resolution (i.e. 3 μm) compared to the focusing by conventional 0.05 NA f-theta lens (i.e. 20 μm). Meanwhile, the proposed focusing setup is user-friendly and flexible to add-on to the commercial laser marking systems saving significant time and cost to the product marking process.

Material and Methods

Natural diamond samples with polished facets in a specific size and cut profile were received from Diamond Centre Wales Ltd. (DCW) for processing. Figure 8 shows the typical schematic drawing of the diamond indicating its various edges, facets and dimensions. The samples were associated to type-1a i.e. containing nitrogen as a trace element/natural impurity within the pure carbon lattice. The size and grade of each diamond were measured as: marquise and emerald cut; depth and width of 2-3 mm, length of 3-4 mm. Approximate total weight of the received samples was measured as 0.3 ct. (i.e. ~60 mg) only.

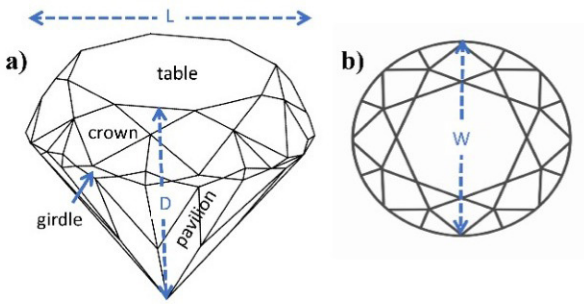

Figure 8: Line diagram of a typical jeweler's diamond—a) showing its various polished facets, (b) top view; L, D and W vectors define length, depth and width of the diamond.

The samples were ultrasonically cleaned in ethanol for five minutes followed by cleaning in deionized water for five minutes and then dried in ambient air. These were held onto a clean glass slide by re-usable putty and orientated so that the facet was able to be laser irradiated and kept at 90 degrees to the laser beam propagation. The laser processed samples were subsequently cleaned using the same process described for pre-irradiation and characterization of the marked area was carried out as follows.

The ultrashort pulses were generated through a fs-laser micromachining system consisting of a Ti: Sapphire oscillator (Spectra Physics Mai Tai) and a regenerative amplifier (Spectra Physics Hurricane) delivering 100 fs-pulses at 800 nm wavelength and 5 kHz repetition rate with the pulse energy up to 200 µJ (1 W). The collimated laser beam (Gaussian profile) was focused through an f theta lens (NA 0.05) to 20 µm spot size on the sample. A linearly polarized fs-laser beam was used, and pulse energy was varied using an attenuator fixed in the optical path. A focused beam traversed continuously on the sample through the motorized XY-galvo mirrors while the "z" direction was controlled by the stage motion controller.

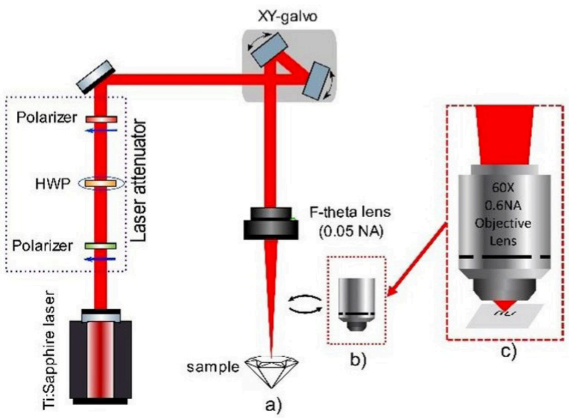

Figure 9: Experimental schematic of the fs-laser system and optics Setup for diamond marking with (a) 0.05 NA f-theta lens, (b) 0.60 NA add-on objective, and (c) magnified view of the laser marking trough the objective lens; HWP is halfwave plate.

Laser micro-marking of the diamond was realized by inserting a 0.60 NA (60X) retractable objective lens into the unfocused beam from the f-theta lens (Figure 9 (c)), allowing the scanning beam from the galvo to fill the objective back aperture and to move within the aperture. The optical design, hereafter referred to as "two-lens focusing system", advanced the focusing capability of the laser system by reducing the original focused spot size to 3 µm (experimentally determined) on the marked specimen enabling writing on the thin facets of the diamond, such as crown, upper girdle and pavilion. The label and the data matrix code required for laser marking were created in the WaveRunner scan control software (Nutfield Technology). A data matrix code (standard ECC 200) with size of 350×350 µm2 was inscribed by scanning the laser beam with, and without the two-lens focusing system. The code redirected to "DCW" after being scanned by QR Scanner (AO Kaspersky Lab, version 1.4.4.173) i.e. an open-source app available on google play store.

The experiments were performed within a range of laser parameters i.e. pulse energy, galvo scanning speed and number of passes given in Table 2. The laser fluence of 2-3 J/cm2 was opted for marking, which also corresponds to the single pulse threshold for diamond ablation.[14] The choice of parameters adopted for laser scanning through two-lens focusing is also given in Table 2. The alphanumeric features were written by continuous scanning of the focused laser beam at variable speed, whereas the data matrix code

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was inscribed by hatching i.e. continuous pulsing of the laser beam with overlap. Meanwhile, the laser scanning speed was enhanced to overcome accumulation effect and prevent potential damage to the diamond due to increased laser intensity (decreased focus spot size) through the two-lens focusing system. The scan speed through two-lens focusing, termed as the "effective scanning speed", was calculated as follows:

Effective scanning speed = (distance between two spots (μm)) × (pulse repetition rate (Hz))

For a laser pulsing frequency of 5000 pulses/sec, and distance of 2.8 μm measured between two immediate spots on marked region, the effective scanning speed obtained on the diamond is 14 mm/sec, against the original galvo speed of 100 mm/sec, i.e. reduced 7-fold approximately after passing through the 0.6 NA objective.

Table 2: Experimental parameters

Table 2
Experimental parameters used for laser marking of diamond

Pulse energy μJ	Focus spot size μm	Laser intensity J/cm^2	Laser scan speed mm/s	No. of pass	No. of pulses/spot	Focusing lens NA
8	20	2.55	2-5	1-2	50	0.05
12	20	3.82	2-5	1	50	0.05
12	3^a	169	14^b	1	1	0.05, 0.60

^{a}final size (experimental) after two-lens focusing; ^{b}effective speed on sample

White-light optical microscopy in bright field/dark field (BF/DF) mode with 10X magnification objectives was used for imaging the marked diamond surface. The depth profile of laser-treated diamond was carried out on a 3D optical microscope (Olympus DSX1000). A detailed morphological examination was performed by Hitachi TM4000+ SEM equipped with both secondary electron (SE) and back-scattered electron (BSE) detectors. The SEM was operated in a low-vacuum mode that enabled direct viewing of the sample without conductive coating. The laser-marked regions were microscopically observed by focusing from top of the sample surface. Raman spectra[15] were obtained using a Bruker Senterra 2 instrument equipped with a 532 nm laser. The laser power was 25 mW and a 50 μm aperture with 20X objective to give a 5 μm spot size. An integration time of 5 s was applied with five co-additions.

Results

Figure 10 shows DF optical micrographs and SEM images (BSE mode) of the laser-marked diamond sample. The result from the sample that was laser scanned by a single pass is shown in Figure 10 (a) indicating "BU" (Bangor University) inscription on the diamond top facet i.e. the table. The size of the inscribed text is 255×155 μm2 with uniform geometry and line thickness. This agrees to the original size (250×150 μm2) of the plain text outline created in the galvo-scanner software. Thickness of the individual line drawn on the diamond is ~20 μm (+/-5%) approximately corresponding to the focussed laser spot size. The unfinished part from the top portion of "B" occurred due to the default delay time between laser start and galvo-scanner movement that was fine tuned in later experiments.

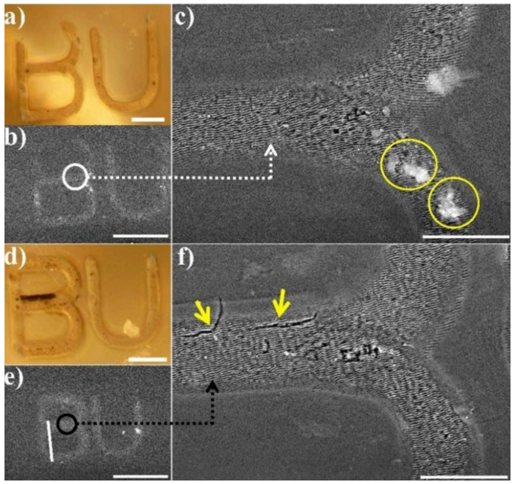

Figure 10: Optical Micrographs— (a) Optical microscope image of marking produced by single laser pass (scan), (b) corresponding SEM image of laser marking, (c) magnified view of marked area, (d) optical image of marking produced by two laser scans, (e) corresponding SEM image of the laser marking, and (f) high-magnification view of the marked area; the scalebar in (a), (d) equals 50 μm, and (b), (e) equals 100 μm, and (c), (f) equals 20 μm; laser pulse intensity through 0.05 NA objective was 2.5 J/cm2.

Figure 10 shows the quality of the laser marking and size of the tracks after a single pass is compared with the corresponding SEM micrographs as shown in (b-c) and (e-f). The bright spots in SEM images (encircled in (c)) are attributed to the putty remains on the sample after cleaning. Fine periodic structuring has been observed with a periodicity below the laser wavelength in the higher magnification images in (c) and (f). This unique nanostructure,

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termed as the "LIPSS", is a universal phenomenon attributed to the interaction of the polarized ultrashort laser pulse with materials, including diamond.[16]

The orientation of ripple pattern was perpendicular to the laser beam polarization direction and the period of the structures (distance between consecutive ripples) was much smaller than the laser wavelength i.e. 800 nm. These features are consistent with high spatial frequency LIPSS (HSFL) model for ultrafast laser processing of dielectric transparent materials. The HSFL were observed at laser intensity near to the ablation threshold of diamond (i.e. 2-3 J/cm2) and with the rest of the laser parameters as given in Table 2. The ablation in a non-absorbing dielectric, such as diamond, is a complex phenomenon which has been explained through various models. The absorption of focused fs-pulses initiates through nonlinear field ionization (multiphoton absorption and tunnelling ionization) and avalanche ionization, resulting in the creation of an electron-ion plasma.[17] Controlling the laser parameters within a narrow range, led to the localized morphological changes required to inscribe high-contrast legible features on the natural diamond surface. On the other hand, marking produced by repeated (2×) laser scanning of the text is shown in (d) (f). Dark colouration and microcracks were clearly visible near the edge of the laser track in the optical image (d) and the SEM micrographs (f) respectively. In addition, there was slight increase in the linewidth that is ascribed to the incubation effect due to accumulated irradiation. Similar results, with microcracks (not shown), were obtained by decreasing the laser scan speed or increasing number of pulses/spots. The precise origin of microcracking in diamond is under investigation, comparison of results with earlier studies indicates this phenomenon may result from diamond to graphite phase transformation[18] with an associated volume expansion and lattice strain[19] induced by the absorption of fs-pulses and accumulation effect. The clear increase in microcracking in the sample marked with two passes of the laser indicates the role that LIPSS has, possibly by increasing absorption of laser energy in the diamond due to an increase in surface area, a change in the material properties (graphitization), pre-existing mechanical deformation (thermal expansion causing plastic deformation), or a synergistic effect. This is further examined in the Raman spectroscopic study in later section to elucidate the effect of fs-laser scanning on structural properties and phase relationship of the natural diamond. In the two-pass example microcracks occurred in the mid part of the "B" (arrow marks in (f) that propagated in the longitudinal and transverse direction to the laser scanning. It may be associated with the

cumulative (4×) laser exposure traversed in the middle of the "B" that led to a pronounced incubation effect in this location of the marking also evidenced by the dark patch visible in (d). This behaviour was absent for the marking traversed by a single laser pass as per the micrographs shown in (a) (c).

Figure 11 shows optical 3D profile of the laser marking traversed by a single laser pass at scanning sped of 2 mm/s and laser fluence of 3.8 J/cm2. The laser ablation profile yielded uniform edge quality of the track with a bell-shaped crater, which is attributed to the Gaussian beam characteristic[20] of the fs laser system. Overall, a track with an average width of 20.6 µm and depth of 0.28 µm was obtained, which corresponds with the spot size of the laser beam through the unaided 0.05 NA focusing lens.

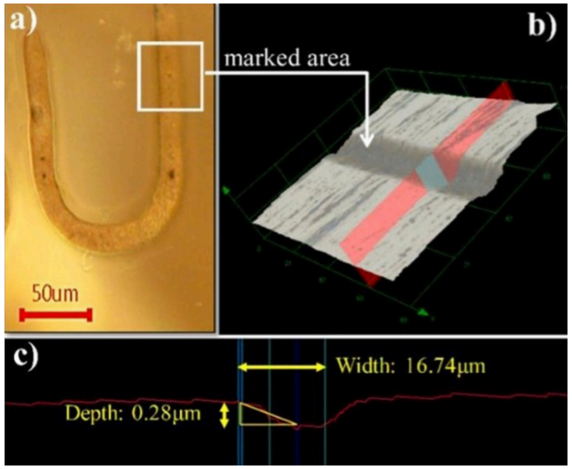

Figure 11: Optical micrograph— (a) Optical micrograph (DF) of the diamond marking produced by single laser scan, (b) corresponding optical 3D profile, and (c) the line profile.

Furthermore, the fs-laser scanning process was extended to inscribe complex geometry such as a data matrix (QR) code (350×350 µm2) through the 0.05 NA focusing lens on the marquise diamond. The capability of writing such patterns was evaluated at variable writing speeds through optical microscopy and results are shown in Figure 12. The surface of the mark generated at scanning speed of 1 mm/s appeared rough and distorted with individual features significantly overlapped (a). This is attributed to the slow speed of the laser scanning leading to an increased interaction time with the diamond and associated with this is the incubation effect. Meanwhile, microcracking on the edges of the geometry was observed, as encircled in (a). Whereas the laser markings inscribed at higher scan speeds yielded different results. Comparing the appearance of data matrix codes, a scan speed of 2-3 mm/s produced the most promising quality of marking without microcracking and substantial darkening of the features in the diamond. In addition, the contrast between the marked and unmarked area was optimum to be recognized by the QR scanner (e). A scanning speed of 5 mm/s resulted in reduced sharpness of the developed features, which is ascribed to the inefficient laser absorption, however, it remained readable through the QR scanner.

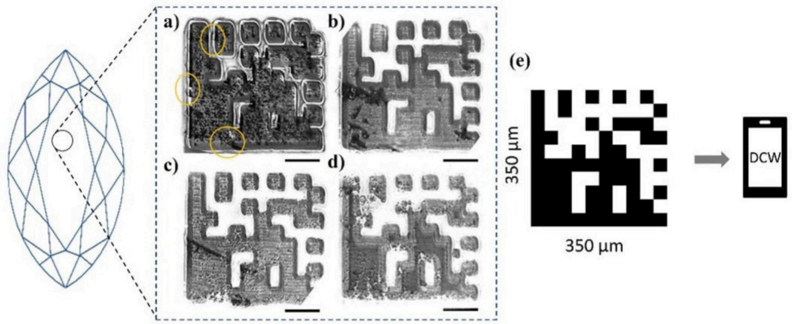

Figure 12: Comparison of optical images— (DF) of the laser inscribed code scanned produced at (a) 1 mm/s, (b) 2 mm/s, (c) 3 mm/s, (d) 5 mm/s scan speed through unaided 0.05 NA lens, and (e) the original data matrix code created in the software, redirects to "DCW" by mobile app; encircled areas in (a) indicate micro-cracks; the scalebar is 100 µm.

We will now consider optical micrographs of the laser inscribed serial number in variable size and data matrix code on the diamond produced by fs-laser scanning (1×) through the two-lens focussing system. The polished diamond facet (pavilion) used for the laser marking is indicated in Figure 12 (b), whereas optical micrograph of the full marking is shown in (c). Surface features of the 8 inscriptions (i.e. text and the code) were observed with high-contrast and uniform line thickness without any microcracking. The minimum size of the serial number marked as "CPE 003-BU" was approximately 25 µm in height without any overlapping between individual spots and lines. Likewise, the size of the data matrix code inscribed on the diamond was 100×100 µm2 from the optical micrograph in (c). The linewidth of the text marking measured from (a) was 3 µm that corresponds to the focused spot-size of laser through a two-lens system. This corroborates

the claimed seven-fold reduction in the focussed beam spot size compared to the unaided f-theta lens (i.e. 20 µm). These results demonstrate the role of the two-lens focusing to control the beam size and laser scanning to generate interesting security features on natural diamond. This also supports realization of inscribing QR-code like symbols, company logos and alphanumeric serials on natural diamonds with a girdle of less than 100 µm across. The remarkable focusing provided by add-on objective was responsible for smaller spot size (compared to the field lens) as well as high-contrast and defect-free laser marking on the diamond. It is noteworthy that the data matrix code in (c) is characterized by a unique substructure formation within the shape boundaries resulting from the continuous laser scanning (hatching) of the geometry and thus absent for the alphanumeric marking. These repeated patterns were larger and appeared dissimilar from the LIPSS observed in our earlier results, which may be formed by high scanning speed with tight focusing of the beam through the two-lens system. Its effect on contrast and overall appearance of the barcode is negligible, however, further research will be crucial to elucidate its microstructural identification and the underlying mechanism. On the other hand, the laser marking size can be further reduced to ~230 nm by using the newly developed super lens by the current team.[21]

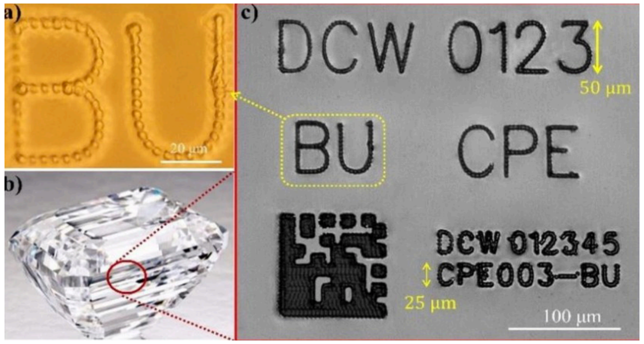

Figure 13: High magnification optical microscope image— (a) of the laser inscribed text produced through two-lens focusing system, and (c) a high-contrast optical image of the laser inscribed code and text on the diamond facet shown in (b).

Ultrafast laser inscription of identifiable security-level marking on the surface of natural diamond has been successfully demonstrated in this work. The delivery of fs-laser beam and scanning through a facile two-lens focusing system enabled defect-free marking of legible serial numbers and data matrix codes 25-100 µm in size and only 0.28 µm deep into the surface of the natural diamond. This design allowed high-contrast permanent marking without distortion of features at optimum pulse energy of 12 µJ and scanning speed of 14 mm/s. A remarkable improvement in the resolution of the produced features was demonstrated by the 7× reduction in the linewidth of the laser marking. Meanwhile, micro-sized defects such as darkening, microcracking or nonuniform features were generated in the diamond at higher or slower scan speeds and/or repetitive laser scanning of the geometry. The results from this investigation provide new opportunities for the diamond and gemstone businesses for unaided and machine-readable security markings, with single digit marking resolution. This work will be expanded to submicron- and nano-marking scale using "Bangor Superlens" technology and generate multi-level security labelling.

Two Lens Focusing

A crucial development in the success of developing the technology used in the Seculuxe laser marking systems for both internal and external marking of the QR code on to a gemstone was the creation of a suitable Plano-convex microsphere lens (PCM).[22]

Complicated structures can be precisely generated through noncontact and maskless laser direct writing. However, the key challenge of laser processing to produce extremely small features is the optical diffraction limit.[23] (In optics, any optical instrument or system— a microscope, telescope, or camera— has a principal limit to its resolution due to the physics of diffraction. An optical instrument is said to be diffraction-limited if it reaches this limit of resolution performance. Other factors may affect an optical system's performance, such as lens imperfections or aberrations, but these are caused by errors in the manufacture or calculation of a lens, whereas the diffraction limit is the maximum resolution possible for a theoretically perfect, or ideal, optical system). To overcome this issue, various laser-based solutions were examined for use in the sub-diffraction nano-texturing required for the project. These techniques were discarded in the early stages due to their low throughput rates and required sophisticated control systems. Research, using a dielectric microsphere as a nearfield lens for super resolution nano-imaging and fabrication has shown excellent results. The optical phenomenon known as photonic nano jet can contribute considerably to laser beam focusing to break the diffraction limit.[24] This method employs a monolayer close-packed particle-lens array to split the laser beam into multiple enhanced focal spots to generate parallel nano-

features over a relatively large area. To realize an accurate and smooth scan patterning process, a gap between focusing lens and sample is a necessary pre-condition. Most research has studied the microsphere lens patterning technique based on nearfield mode that is in contact or within an incident wavelength distance. Recently, manipulation of single microsphere lens by laser trapping and tip-based scanning techniques were demonstrated for complex nano-pattern processing.[25] Our research resulted in a major step forward in laser-direct patterning systems that can perform large-area subwavelength surface processing with user-defined patterns. A new superlens design, namely a compound lens consisting of a Plano-Convex lens and a Microsphere lens (PCM), was proposed. The PCM superlens can be implemented as an optical probe to generate subwavelength focusing at a micrometre distance. With the assist of a side-view monitoring system and high-resolution nano-stage, we can achieve precise control and monitoring of the working distance (WD) between probe and sample during scan patterning process. Meanwhile, the performance of a PCM lens at different WD was theoretically and experimentally evaluated. The capability of arbitrary pattern fabrication was realized. It is an objective-free, low-cost, highly efficient and flexible system with high completion for large-area sub-wavelength nano-patterning, which should satisfy the growing industrial demands in laser nano-patterning.

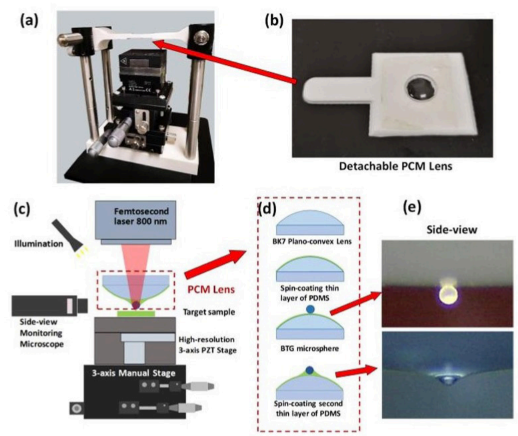

Figure 14: PCM lens and system set up for laser nano-patterning—
(a) Photograph of an actual system set up
(b) Photograph of an actual detachable PCM lens module
(c) Schematic of the PCM nano-patterning system
(d) Fabrication of a PCM lens
(e) Side view of a PCM lens

QR Code Reader/Scanning Tool
Having developed the technology to place micrometre scale QR codes on the surface of gemstones, using the power of a finely focused laser beam a methodology and technology had to be developed to facilitate the reading and digital machine reading of the QR code. The micro-scale of the code prevents it spoiling the aesthetics of the stone, as it is smaller than the eye can see, and the machine-readable nature of a QR code means that there is no need for specialised training to read it along with the removal of the possibility for human error in any data entry required. It should also be a significantly faster process. The caveat here is that as the code is micro-scale, a device, system or process needed to be developed that will allow an untrained individual to find and read the QR code. This was the basis for the following phases of the project.

Polarised Light
When transparent polymers are viewed under a polarised filter, it is possible to see stresses and strains within the material due to the distortion of light as it passes through the material. It was posited that something similar might happen within the gemstone due to the localised heating effects of the laser. It was hoped that this might provide a clue at the macroscale as to the presence and/or location of the QR code.

Investigation using polarised filters did not reveal any noticeable, and therefore useable, sign-posting effects. There may well be such effects at a lower scale, but since this would require detection and location of the QR code in the first place, the subsequent use of a polarising filter was considered a redundant branch of research and was dropped at this point.

UV Light
Diamonds are known to fluoresce under UV light, and it was hypothesised that the localised heating and modified topography effects of the QR engraving might noticeably distort the returned UV light signal, again as a method for signalling the presence and/or location of the QR code at the macroscale. For this investigation a UV torch was used to illuminate samples, but there were no noticeable effects to indicate a difference between marked and unmarked stones, leading to this line of research to also be abandoned.

Shadow Casting
Another theory investigated was to make use of the transparent nature of the diamond. The hypothesis was to shine a powerful light source through the stone at close range and place a screen at a distance for the light to fall on. Any distortions in the light such as marks or scratches would effectively be magnified and cast as shadows (or darker areas) as they changed the amount of light passing through their region. This technique showed some promise but not enough to warrant further investigation. Small blemishes and marks did show up as shadows, along with the edges of each of the cut faces of the stones, however the 3D nature of the stone made it difficult to focus them. Furthermore, the light source, an ultrabright LED, was not powerful enough to make clear features. Additionally, the distance needed to magnify microscale sufficiently was considered to be impractical.

Digital Microscopy
This was considered to be the most conceptually simple avenue for more detailed investigation and research and indeed became the central focus of the project. A cheap, simple digital microscope was procured, and it soon became evident that it could resolve the micro-scale QR codes. The challenge was finding the codes in the first place, as the whole surface of the stone needed to be observed, securing the stone so it didn't move whilst also making it able to be manipulated to search for the code, and focusing successfully on the surface of the transparent material rather than looking within or through it.

This technique demonstrated the most potential for success, and so it was selected for further development within the timescale of the project. The first challenge was to reduce the difficulty of finding the QR code. This was done by agreeing that engraving should be limited to just the table of stones (the flat section) and next to one of the star facets.

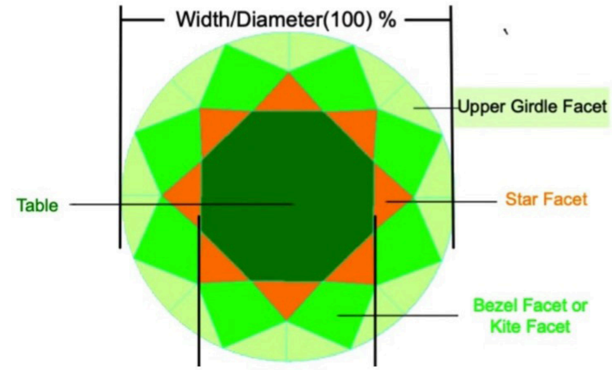

Figure 15: The table and star facets of a diamond

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This considerably reduces the surface area that needed to be scanned and has the advantage of placing the stone on a flat section so that it can remain stable during the investigation. Additional examination with the microscope, which used reflected light from its aperture, showed that it performed better (provided better imagery) if the light was passing through the stone (transmitted light) rather than reflecting off its surface. This was discovered via use of an externally held ultra-bright LED. This also allowed the angle, direction and distance of the light to be adjusted, and it seems that this has a significant impact on the quality of the results, as the better images seemed to come from times when the external light was refracting through the QR code and providing a high contrast against the background material. Given that all stones are differently shaped, and each QR code will be differently placed, this suggests that the external transmitted light-source should be able to be manipulated by the user to improve QR code accessibility and readability.

The need for transmitted light required a further aspect of the design to be developed: a pinhole. If the light passing through the stone was allowed to pass around the stone, it blinded the microscope and rendered the returned images completely unusable. Therefore, a pinhole was placed between the stone and the microscope, forcing the light to pass though the stone before entering the microscope aperture. This returned some high-quality imagery of QR codes with some very low-tech apparatus, suggesting that development of a more sophisticated system would provide equal, if not higher, quality imagery and an improved user experience.

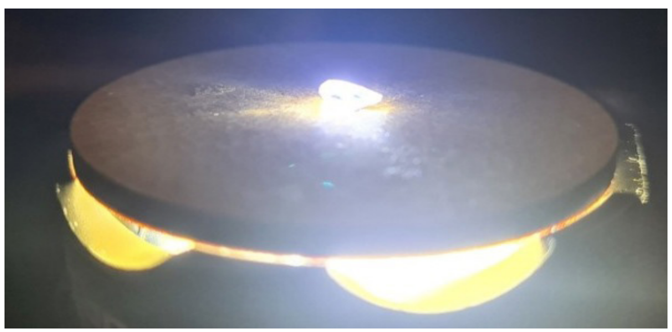

Figure 16: The pinhole

Figure 17: The view through the pinhole

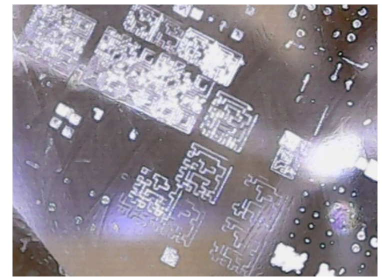

Figure 18: Enlargement of the view through the pinhole

Once the pinhole process was established as a viable option a tool was designed to incorporate the idea into a digital microscope.

The project's premise, when it comes to the reader/scanner, was to keep the instrument as universally available and affordable as possible. The microscope of choice was a very affordable (£18.00, $22.00) handheld digital microscope with a USB cable connection similar to the one shown in Figure 19.[26]

Figure 19: Handheld digital microscope

A mount for the scanner, along with adaptors for holding the stones and focusing the pinhole on the diamond was also designed and for cost, speed and ease of prototyping 3D printed.

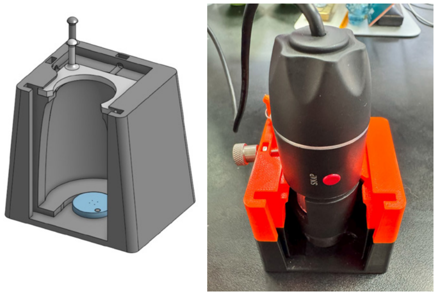

Figure 20: Desk top digital microscope scanner mount and observation table with micro adjustments

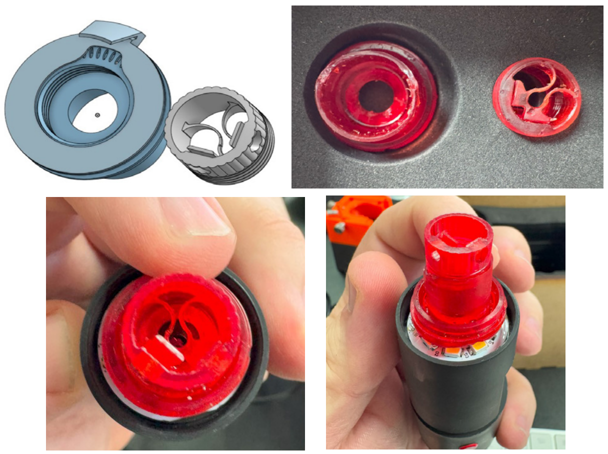

Figure 21: Portable micro hand-held scanner mounts for USB microscopes

It is also possible to use the camera on a mobile device with a magnifying adaptation to read the QR code. This technique has the added advantage of giving easy and direct access to the necessary online data held in the blockchain about the diamond being read/scanned.

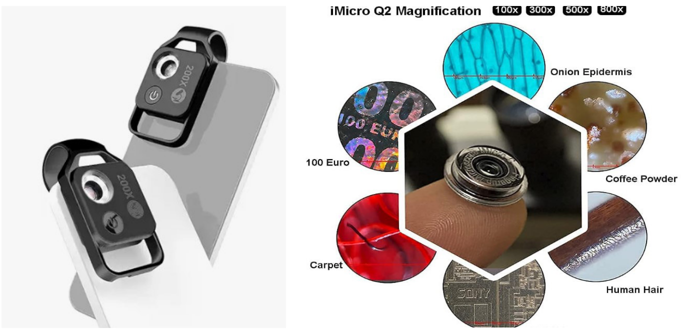

Figure 22: Mobile phone microscope adaptations

In addition to the physical development of this apparatus a portion of the project time was used to develop the digital conversion side of the process, in terms of extracting the QR code from the image. Python,[27] a coding language, was used along with Jupyter Labs[28] notebook function, to demonstrate a basic workflow and show how it might be used and developed further.

The OpenCV[29] (Computer Vision) library was used to read the image file, and OpenCV's thresholding functions were used to convert the image to a binary format.

What is Thresholding?

You've probably encountered images where certain parts are much brighter or darker than others, right? Thresholding is a technique in image processing that helps you distinguish these regions by converting grayscale images into binary images. Essentially, it's about setting a cutoff point— known as the threshold— and anything above this point becomes white, while anything below it turns black.

For example, if you're working on detecting text in a scanned document, thresholding can help you isolate the text from the background by turning the text black and the background white. It's a straightforward yet powerful tool, especially when you need to simplify an image for further analysis.

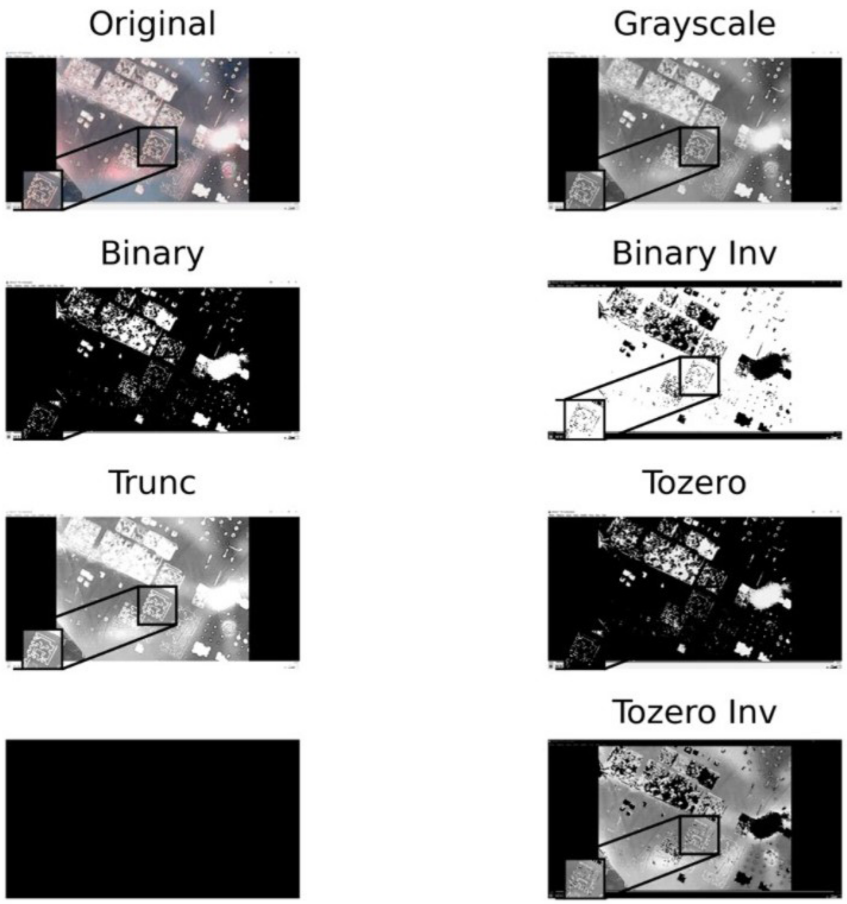

Figure 23: Various threshold filters

The inverted binary threshold function seemed to produce the most acceptable results, so that image was selected and the relevant portion isolated. The Adaptive Threshold function was also tested to demonstrate the extensive extraction that is possible if the parameters are optimised correctly.

Figure 24: Inverted binary image

The resulting isolated image section represents the clarity that can be achieved when extracting QR codes from the microscopy imagery process developed.

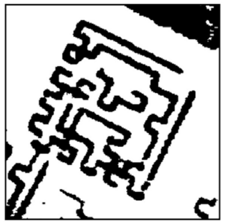

Figure 25: The resulting, readable, QR code after thresholding

CONCLUSION

These various research strands reported here have all been collated and refined resulting in the creation of the first two Seculuxe 'proof of concept' laser marking systems and scanners/readers being built and undergoing real time trials at Diamond Centre Wales before being reverse engineered ready for volume manufacturing. Figure 26 is an image of the first working prototypes undergoing shakedown trials early in 2025.

Figure 26: Seculuxe technology prototypes under test

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