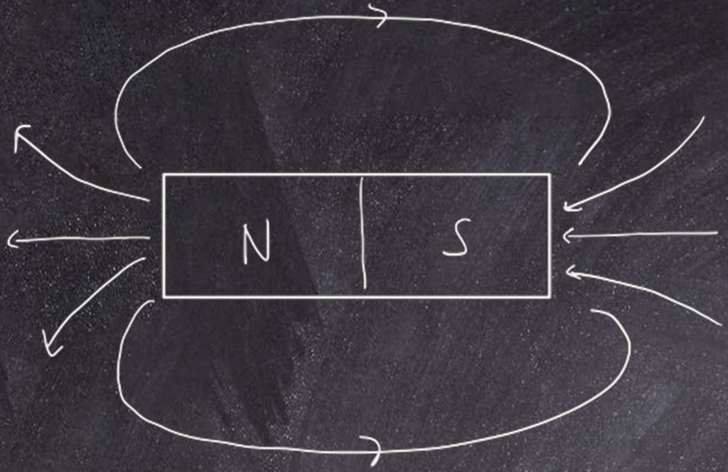
Physics Department Newsletter

Volume 1, Issue 02

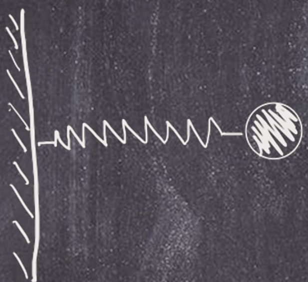


$$\nabla \cdot \vec{E} = \frac{1}{\varepsilon_0} \rho$$

$$\nabla \cdot \vec{B} = 0$$

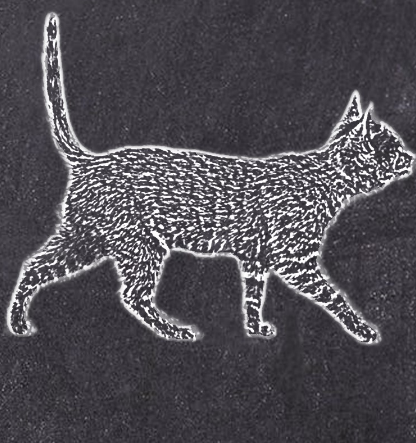
$$\nabla \times \vec{E} = -\frac{\partial}{\partial t} \vec{B}$$

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \mu_0 \varepsilon_0 \frac{\partial}{\partial t} \vec{E}$$



$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{x}}\right) = \frac{\partial L}{\partial x}$$

$$m\ddot{x} = -kx$$



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HERIOT WATT UNIVERSITY
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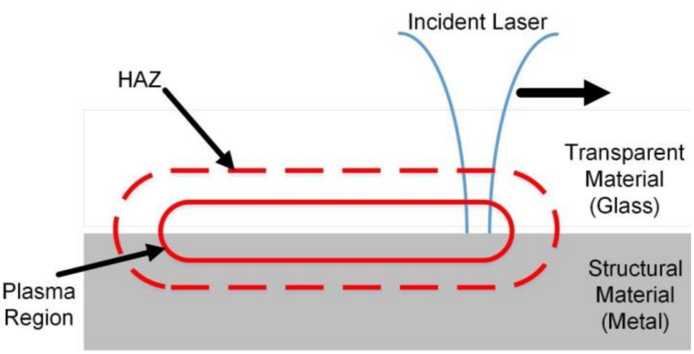
From Concept to Industry: Ultra-Fast Laser Welding

Dr. Richard. M. Carter, Applied Optics & Photonics Group

Personally, I have always found the most engaging part of working in science to be at the applied end. There is nothing like being presented by a real-world problem (often by a company) and attempting to find some new application of physics or engineering to try to solve it.

Working within the Applied Optics and Photonics group there is certainly plenty of scope to scratch my need for applications as almost all the research we do is sponsored by a company or some sort of end user. Of course, creating a new laser manufacturing process does not happen overnight – indeed it can be a very long road from idea to application – and I thought it might be interesting to explore this via an example which I have been involved in from start to finish (if process development can ever really be called finished): our work on dissimilar material welding.

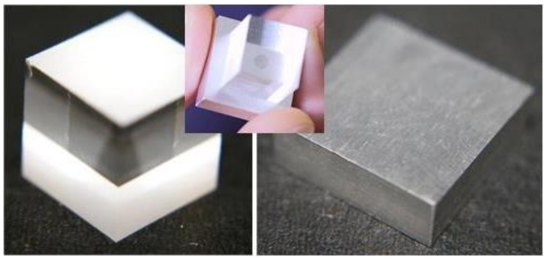


Schematic illustration of ultra-short pulse laser welding. The incident laser is focussed through the glass onto the metal surface. By translating the laser along the interface a weld is formed from an inner plasma affected region and an outer heat-affected zone (HAZ).

Many of you may well be familiar with the general principle here (I tend to explain it to people at the drop of a hat whether they are interested or not!). Take two materials, one of these needs to be transparent (like glass or a crystal) since we need to focus the laser through it. Then use an ultra-short laser (fs, 10-15 or ps, 10-12 s pulse durations) focussed onto the interface to generate a plasma which is made from both materials. Providing there is reasonably good contact between the two this plasma will remain in place and as it cools it will form a weld between the two materials.

Thanks to the short pulse length and tight focussing the heat thus generated can be confined to a remarkably small area, typically 100's of micrometres. On this scale thermal expansion is not really an issue hence it is possible to weld together materials with radically different thermal properties (like glass and metal). Something which is essentially impossibly by other means. Of course, you could just glue it (and companies do just that) but applying an adhesive in a reproducible manner is much more difficult than you might think; and there are issues with how adhesives behave over time. As such there is a great deal of interest in a wide range of industries for a method to join dissimilar materials without needing to use a glue, frit, solder or other method that introduces a new material.

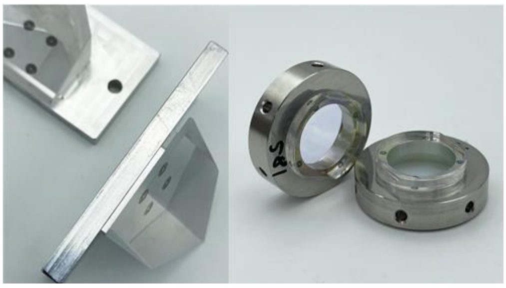
The first work in this area came out of Japan with a series of papers from Kazuyoshi Itoh's group at Osaka. In 2005 they demonstrated that it was possible to weld two transparent materials using a femtosecond laser and two years later glass to silicon by essentially the same process. However, the starting gun for dissimilar material welding would not really be fired until May 2008 when they published a paper reporting welding of copper to glass using a femtosecond laser. This was a significant result since copper and glass (silicon and oxygen) should not really interact in a useful manner to form a weld structure i.e., they demonstrated that truly dissimilar materials could be joined in this manner.



Example test parts for project Ultraweld – 10 mm glass cubes and 15 x15 x 5 mm metal coupons – insert example of a welded glass-metal pair with a typical 2.5 mm Ø spiral weld.

This paper reached the desks of Duncan Hand and Robert Thomson who setup a small project in 2012 to have a look at this on behalf of Renishaw. This is where I, still fresh from my PhD with a distinctly damp set of ears and a ~515 nm glow, came in as a post doc.

It took a few months, but we managed to not only weld copper to glass using a picosecond laser but a number of other materials as well (stainless steel, silicon, aluminium, sapphire, etc.). However, these were only proof of principle demonstrations; the welds were not terribly strong, the setup rather crude and the metal surface needed to be polished to a mirror finish to get it to work (this would turn out to be a continuing problem).

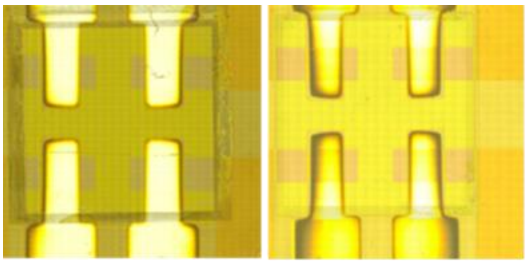


Demonstration welded parts. Left: BK7 prism wedge welded to Al, 24 x 24 mm footprint 1-18 mm thickness. Right: quartz waveplate welded to stainless steel Ø 12.7 mm, 2.1 mm thick.

What then followed were a series of industry sponsored projects within the EPSRC Centre for Innovative Manufacturing in Laser Based Production Processes with Renishaw and later Selex/Leonardo to look at specific material combinations and try to develop a useable process. So, we got to work looking at specific materials, developing a process to evaluate the strength of the bonds, and to see if we could relax the surface finish requirements (polishing is quite expensive). By 2014 we had expanded to include a PhD student (Jinyong Chen) and managed to publish a paper demonstrating welding on a range of material combinations with some preliminary data on process yields and strength.

The issue, we were finding, was that the welding process creates a defect in the glass above the weld region. As a result, the welds nearly always failed in the glass and, since glass is a brittle material, this leads so a significant statistical spread in yield and strength for any process parameters we attempted. Hence, we needed to carry out ~ 20 tests for each processing parameter to get statistically relevant data – expensive both in terms of time and materials.

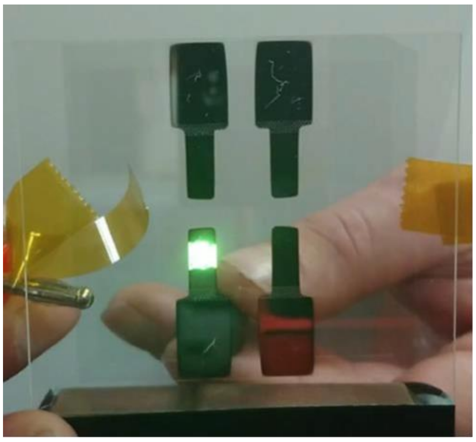
Since it was not practical to try to test everything the decision was taken to narrow the search to just three optical materials of significant interest to Leonardo: BK7 and SiO2, bonded to Aluminium. Nevertheless, this took the best part of two years (2016-2018) to get enough data and develop something resembling an optimised process. The good news was the strength of the bonds appeared similar to that of adhesives; the bad news is we could not at that point get above ~ 80% yield – far too low for an industrial process.



Examples of thin flex OLED bonding.
Left: continuous weld, Right: discontinuous weld. In both cases the welds pass through regions of glass with and without layers of ITO and Al.

Improving process yields in a research lab setting is often very difficult as there are multiple demands for both time and equipment, and we are not really setup to be a production facility – it is a research lab after all. Hence we felt it about the right time to take the project to the next step – try to port it out of a research lab and into industry. This is often the hardest step when trying to develop a new application – usually university research stops well short of a fully industrialised process and there are few companies able, or willing, to make the multi-year massive investment to finish development. What is generally needed is some sort of bridging project – and there are a number of specific funding schemes to support this.

But who would develop an industrial process? It was outside of the scope for the university lab do so directly and Leonardo, as an end-user, were very supportive but fundamentally were not intending to develop the process themselves – this was something that they would outsource for production. What was needed therefore was a company specialising in manufacturing laser systems for industry – the sort who could produce a prototype laser. This is where Oxford Lasers came into the picture. With them taking the lead we applied for Innovate UK (a government research funding group for funding specifically to make the leap from university to industry). Thus was project UlraWeld born, a three year £1.2M project with four companies and two “research organisations” (HWU and the Centre for Process Innovation). By this stage Robert Thomson had moved on to other things (something about stars in his eyes/detectors) and Daniel Esser had joined the team in his capacity as Leonardo Research Chair in Laser Device Physics and Engineering. The goal here was to try to construct a prototype welding machine based on the glass-aluminium process we had developed, and specifically apply it to making parts for industrial lasers. At the same time, we were going to investigate two other welding processes: thin flex glass for organic LED encapsulation and stainless steel to quartz welding – two areas that Oxford Lasers had identified as having significant potential.



Demonstration of operating OLED sealed with discontinuous welding pattern.

Almost immediately after the project started the plans went somewhat out of the window. I had managed to make the jump to an academic position, hence a new post doc – Paulina Morawska was recruited to do the real lab work.

In addition, it started to become very clear that the issues with process yield were down to reliable cleaning of the materials (an issue that Paulina found a solution to on virtually day one), the consistency in the size of the optics to within 100 µm but also to the surface finish on the metal parts. We quickly found that the relevant standards (ISO's) for surface roughness on metals were not really suitable for this process so we set about attempting to make our own definition of what roughness could be welded.

C-Series Oxford Lasers system – the basis for the ultra-fast laser welding prototype

If any of you have ever looked into surface roughness measurements of shiny metals, you will know that this is a rabbit hole. A rabbit hole which should have a warning sign on it and perhaps a large, barbed wire fence to prevent the un-wary from blithely strolling in. Three years later and we are still not quite sure how to define a weldable surface – and certainly not a definition that colleagues in industry would find meaningful. Instead, we have managed to define a machining process that, if done correctly, provides a weldable metal material finish.

In the end thanks to heroic efforts by Paulina, a second and third PhD student Samuel Hann and Nathan Macleod, and toward the end of the project another post doc, Adrian Dzipalski, as well as numerous undergraduate student projects inspired by the challenges, all the project goals ended up being met by late 2020. A process for welding thin glass (100 µm) another for stainless steel to quartz, and Oxford Lasers build a prototype laser welding platform which they used to produce some demonstration parts. And there we have it eight years, multiple academics, three post docs, three PhD projects, five companies and a massive amount of time, effort and skill from the research team; from proof-of principle to prototype industrial welding process.

Fabios "Tricky Question"

Dr. F Biancalana

In the latest issue of our Newsletter, I asked a simple mathematical question: "What is the sum of all the integers from 1 to infinity?" In other words, what is the final result of the infinite sum (let us call it "C" from now on) , $C = 1 + 2 + 3 + 4 + \cdots$ up to infinity?

Intuition tells us that the sum C explodes to infinity, or, as mathematicians say, the sum does not "converge" to a finite number. This reasoning is absolutely correct, if we only know about real numbers – after all this is what we learn in school when studying infinite series. However, when complex numbers are considered, the result of this infinite series could be very different.

However, the great Indian mathematician Ramanujan found a simple and mind-blowing way to express C as a finite number, without using complex analysis – so let us start with his idea first. We already know that

$$C = 1 + 2 + 3 + 4 + 5 + 6 + \cdots$$

Now let us multiply by 4:

$$4C = 4 + 8 + 12 + 16 + 20 + 24 + \cdots$$

And now let us subtract 4C from C:

$$C - 4C = -3C = 1 - 2 + 3 - 4 + 5 - 6 + \cdots$$

If you have the patience, you can easily verify the above sums by taking just a few elements of the sum and doing the subtraction above. Now for the important bit of real analysis: let us expand in Taylor series the function $1/(1+x)^2$; one has, for small values of x:

$$\frac{1}{(1+x)^2} = 1 - 2x + 3x^2 - 4x^3 + 5x^4 - 6x^5 + \cdots$$

In the limiting case of $x = 1$, this Taylor series is identical to the above series for $C - 4C$. Substituting $x = 1$ to the Taylor series we immediately see that

$$-3C = \frac{1}{4}$$

And therefore, our original infinite sum:

$$C = 1 + 2 + 3 + 4 + \cdots = -\frac{1}{12}$$

This is it! Our infinite sum does not diverge, and the final value is not an integer, and it is not even a positive number, but a negative one!! This is really surprising – but is it correct? Without going into details, one could argue that some steps above look a bit suspicious – especially the part where we take the Taylor series and extend it to $x = 1$, whereas in a Taylor series the expansion only makes real sense for $x < 1$.

That the result is correct can be understood in a large variety of ways, one of them is by using a complex function called the *Riemann Zeta function*. I cannot describe this method here because it will take too much space, but please search it on the internet if you are curious about the so called "Zeta function regularization".

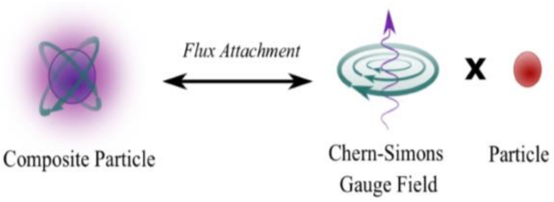
The fact that $1 + 2 + 3 + 4 + \cdots = -1/12$ has surprising consequences in high-level physics. For example, this weird sum is used when one wants to know what happens to two metal plates when they are placed very close to each other. Quantum mechanics predicts (by using our sum!) that the two plates attract each other, something known as the *Casimir effect*. Another very deep consequence of our surprising sum is found when studying String Theory, the most popular and quoted theory of everything. The simplest version of string theory predicts that, again due to quantum effects, spacetime has 26 dimensions, many of which cannot be seen: a result that is derived precisely by using our infinite sum of integers.

As always, if you have any questions on Fabio's "tricky question" then you can contact Dr. Biancalana. Stay tuned for a new "tricky question" in next months issue!

Is it a Boson? Is it a Fermion? No! It is an Anyon!

Dr. P. Öhberg, Quantum Optics & Cold Atoms Group

Imagine a cold gas of atoms. So cold that its temperature is a few nano-Kelvin above the absolute zero. These atoms are neutral, with no charge. At these low temperatures we have to describe the millions of atoms using quantum physics. The atoms behave in a most peculiar fashion at these low temperatures. They become a superfluid with some surprising dynamics. The gas can for instance only rotate in a quantised manner, and flow past objects in a frictionless manner. If we shine light on the atoms things become even weirder. If we choose our incident laser cleverly, the gas starts to behave as if it had an effective charge and thinks it is subject to a synthetic magnetic field!



A schematic view of the composite particle picture. Flux attachment is a mechanism by which a particle captures a magnetic flux quanta and becomes a composite entity. These composites might have different properties from the bare particles, in particular they can be Anyons.

There are two types of particles in nature: bosons and fermions. Bosons tend to lump together and prefer to occupy the same quantum state. They can form superfluids like the atoms in our cold gas for instance. Fermions on the other hand are different. You cannot have more than one fermion in each quantum state.

The Quantum Optics and Cold Atoms group in IPaQS has recently showed that the combination of ultracold atoms colliding with each other, and a laser which interacts with the internal structure of the atoms, can give rise to a phenomenon called flux attachment. This effect can be understood as having a local excitation in the atomic superfluid where there is a synthetic magnetic flux attached to it. We can think of this as a composite particle, but curiously this composite particle does not behave as a boson nor a fermion; it is something in between. We call this particle an Anyon. These particles have strange properties. They cannot be isolated, and only exist as an exotic excitation in a larger environment and as a result of collective behaviour of the underlying quantum fluid. To understand the properties of these Anyons we need to work with some fascinating maths closely connected with topology.

If you want to read more, you can check out this paper on synthetic flux attachment.

Heriot-Watt Physics Society

Kate Robertson, 5th Year MPhys Chemical Physics

The Heriot-Watt Physics Society is still operating this academic year, running various social and academic events. The committee members are: Michael Penman (president), Kate Robertson (secretary), Alex Burnside Ribera (treasurer), Faris Redza (academic coordinator), Nathan Graham (second year representative), Henry Ward-Raatikainen (second year representative) and Harry Coyle (third year representative). Last semester we held various social events on our discord channel, and we had Dr. Alessandro Fedrizzi give our first very successful colloquium of the year on the topic of "Quantum technology and the Foundations of Reality". This semester we had Dr. Jonathan Leach present our second colloquium, "Imaging at the speed of light" in week 5. In consolidation week we ran a quiz for the students and academic staff, with Dr. Paul Dalgarno, Dr. Lynn Paterson and Michael Penman's team being our overall winners. Our next academic event this year is a colloquium given by Dr. Bill Macpherson on how Scotland played its part in efforts to "weigh the earth". This will be held on Wednesday week 7 (24th Feb) at

3pm on the Physics Society teams page. Anyone who wishes to get involved in the society feel free to contact any member of the committee by email or through our Facebook page.

Right: Last years student vs. lecturer games night – with Drs. Lynn Paterson and Richard McCracken winning the competition

List of Latest Research Output

Process Optimization for 100W Nanosecond Pulsed Fiber Laser Engraving of 316L Grade Stainless Steel.
Dondieu, Stephen; Wlodarczyk, Krystian L.; Harrison, Paul; Rosowski, Adam; Gabzdyl, Jack; Reuben, Robert L.; Hand, Duncan P.
In: Journal of Manufacturing and Materials Processing, Vol. 4, No. 4, 110, 12.2020.

Complete mapping of the thermoelectric properties of a single molecule.
Gehring, Pascal; Sowa, Jakub K.; Hsu, Chunwei; de Bruijckere, Joeri; van der Star, Martijn; Le Roy, Jennifer; Bogani, Lapo; Gauger, Erik; van der Zant, Herre.
In: Nature Nanotechnology, 16.12.2020.

Diffraction-limited integral-field spectroscopy for extreme adaptive optics systems with the multicore fiber-fed integral-field unit.
Haffert, Sebastiaan Y.; Harris, Robert J.; Zanutta, Alessio; Pike, Fraser A.; Bianco, Andrea; Redaelli, Eduardo; Benoît, Aurélien; MacLachlan, David G.; Ross, Calum A.; Gris-Sánchez, Itandehui; Trappen, Mareike D.; Xu, Yilin; Blaicher, Matthias; Maier, Pascal; Riva, Giulio; Sinquin, Baptiste; Kulcsár, Caroline; Bharmal, Nazim Ali; Gendron, Eric; Staykov, Lazar; Morris, Tim J.; Barboza, Santiago; Muench, Norbert; Bardou, Lisa; Prengère, Léonard; Raynaud, Henri- François G.; Hottinger, Phillip; Anagnos, Theodoros; Osborn, James; Koos, Christian; Thomson, Robert R.; Birks, Tim A.; Snellen, Ignas A. G.; Keller, Christoph U.
In: Journal of Astronomical Telescopes, Instruments, and Systems, Vol. 6, No. 4, 045007, 23.12.2020.

Transient Optical Properties of CsPbX3/Poly(maleic anhydride-alt-1-octadecene) Perovskite Quantum Dots for White Light Emitting Diodes.
Xu, Jian; Zhu, Liang; Chen, Jia; Riaz, Saba; Sun, Liwei; Wang, Ying; Wang, Wei; Dai, Jun.
In: Physica Status Solidi - Rapid Research Letters, 01.12.2020.