**Article for Breaker : Diamonds Continue to Amaze**

**General introduction**

A team from Imperial College London and University College London recently demonstrated [continuous stimulated microwave emission at room temperature](https://www.nature.com/articles/nature25970), in other words a **maser** – an acronym of ***m****icrowave* ***a****mplification by* ***s****timulated* ***e****mission of* ***r****adiation* – that creates identical copies of microwave photons (the individual quantum packets of energy that make up electromagnetic waves).Similar to lasers except they emit microwaves, masers were invented in the 1950s. However, unlike lasers which have made an astonishing impact in medicine, manufacturing, science, communications and engineering – masers have developed little since their invention because they need to be cooled to cryogenic temperatures close to absolute zero (-270 °C). Despite this, they are excellent amplifiers and used to detect incredibly weak signals from space like the cosmic background microwave radiation and signals transmitted by the Voyager space probes.

**Introduction to study**

In 2012, members of the same team [demonstrated a maser](https://www.nature.com/articles/nature11339) using the organic molecule pentacene – five benzene rings stuck together. This maser was the first to operate at room temperature, needing a powerful yellow laser to energise the pentacene molecules, but only produced pulses of microwaves that lasted less than a thousandth of a second. If this maser could have worked continuously, the pentacene crystal would have melted because it has a low melting point and is terrible at conducting away the heat generated by the laser. The search was on for alternative materials that could drive a maser continuously and withstand the heat generated by energising laser.

**Methodology**

We wondered why the first masers, that used ruby (aluminium oxide crystals containing trace amounts of chromium), needed to be cooled to super-cold temperatures at all. Masers and lasers require a ‘population inversion’ where there is an excess of electrons in a higher energy state than a lower one. Stimulated emission happens when a photon (tiny particle of light) causes an electron to drop down from the high energy state to the lower one and emit an additional identical photon in the process. Vibrations in the crystal also cause electrons to jump up or down, destroying the population inversion. Cooling reduces the effect by making the crystal ‘quieter’ with fewer vibrations. Theory agreed with the observed effect in ruby and suggested that materials made from carbon and silicon would suffer less from this effect. Further research revealed a rich treasure trove of work on diamond, where special impurities combined with imperfections in the crystal structure had useful properties. Another bonus is that diamond has the highest thermal conductivity of any material and is mechanically robust.

**Results**

We used a synthetic diamond grown in a nitrogen-rich atmosphere. It was then exposed to a high-energy electron beam to knock out some of the carbon atoms, creating holes or ‘vacancies’. The next step heated the diamond up to 800°C, allowing the nitrogen impurities and vacancies to move around and meet to form a stable arrangement called a nitrogen-vacancy centre. A population inversion was created in the diamond by shining bright green laser light on it and placing it in a magnetic field. The diamond was placed in the centre of a sapphire ring inside a hollow copper cylinder. This structure – called a cavity - acted like a mirror, reflecting and concentrating the microwaves emitted by the maser and also increasing the likelihood of stimulated emission. This ‘mirror’ was key to making the maser work and getting above ‘threshold’ – where the maser emits more microwave power than is absorbed by the surrounding structure or lost through radiation. So, the cavity had to be carefully designed. The maser emitted continuous microwave radiation at 9.2 GHz (wavelength of 3 cm), but this frequency could be varied by changing the magnetic field.

**Conclusions**

To conclude, we were able to demonstrate a maser that worked continuously at room temperature using a synthetic diamond with specially engineered defects called nitrogen-vacancy centres, a carefully designed microwave cavity (‘mirror’), a green laser and a magnet. The diamond maser could find application as accurate atomic clocks for global positions systems, ultra-sensitive magnetic field sensors and super-quiet and sensitive amplifiers. The new maser could also find a range of applications ranging from medical imaging to body scanners at airports; they could also perhaps play a central role in improving the sensors used to detect explosives from a distance, or perhaps even quantum computing, testing the boundary between classical and quantum physics and a new generation of technologies based on the quantum phenomena of entanglement and superposition.