# NOVEL SPRINTRONIC DEVICE TERAHERTZ MAGNON LASER

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## *A. Why THz radiation – and why not yet*

The terahertz range of frequencies, generally accepted as being within the frequency region between $3 \times 10^{11}$ to $3 \times 10^{13}$ Hz (having wavelength in a vacuum from one millimeter to ten microns), presents a new frontier for solid-state electronics and their application. Since THz radiation spectrum exists between microwave spectrum (used in microwave electronics) and infrared spectrum (used in infrared optics), and corresponds to the molecular vibration frequencies in complicated biological objects, the potential and emerging applications of terahertz electronics are myriad and vast. When adequately supplied and sensed, THz radiation can be used as a powerful tool for through-the-wall imaging, since it can penetrate through thick dry wall and other common building materials. It can also be used to detect threatening munitions from across a battlefield, for bio-molecular sensing and biomedical analysis, to detect poisonous and biological substances, in medicine as a sensor for cancer cells and other real-time diagnostics, for environmental monitoring and radio astronomy, and in semiconductor lithography and a host of security- and defense-related applications.

Despite the opportunities, the lack of a high-power, narrow-band, tunable and portable THz source remains the most significant limitation of modern THz systems. The best current commercially available techniques for generation and modulation of THz radiation use ultra-short optical pulses to generate a very rapid change of the conductivity of a semiconductor sample. These techniques allow one to obtain a broadband, pulsed radiation in the THz range, at power levels on the order of microwatts, but without significant tunability; they provide faint, shotgun energy where highly tuned and high power rifle shots are required.

To come at these problems and opportunities from an entirely new direction, we have invented a novel spintronic device that can generate narrow-band, coherent THz pulses, with tunable frequencies at high efficiency and at power output levels on the order of a milliwatt and greater.

## *B. Technical Background*

As a brief introduction to our invention, we first discuss the quantum nature of magnetism and Spintronics. The electrons that carry charge current in electric circuits also have the quantum characteristic of “spin” and, associated with spin, magnetic momentum. Spin is a purely quantum phenomenon, and it can point only “up” or “down”. In non-ferromagnetic samples, the spin of electrons is usually randomly oriented and does not play a material role in the behavior of the device. However, in ferromagnets, with inherent magnetization (spontaneous polarization), the electron energy strongly depends on their spin direction, and the electrons are partially or fully spin-polarized, i.e., their spins predominantly point “up”, which is the direction of the magnetic moment.

Exploitation and manipulation of the spin and charge of electrons is called Spintronics, a new field that emerged in the 1980s from the discovery of Giant Magnetoresistance[1] in a device consisting of at least two ferromagnetic layers separated by a non-ferromagnetic spacer layer. Spin can play an important role in device function: the electrical resistance of a Spintronic device depends on the mutual orientation of the magnetization vectors in the ferromagnetic layers. Such a device can also act as a magnetic field sensor.

### *C. Magnon laser*

The core effect behind our invention is based on achieving magnon lasing in ferromagnets with fully spin-polarized electrons[2]. Magnons are elementary wave-like excitations in magnetic materials. The energy of magnons, like the energy of electrons, depends on their momentum. The excitation of a magnon reduces magnetization. In a state of equilibrium, the number of magnons increases with temperature. At certain temperature equal to the (material-dependent) Curie temperature (Tc), there are so many magnons that no magnetization is possible, that is magnetization tends to zero. Thus, a ferromagnetic state exists only at temperatures lower than the Curie temperature.

An electron with spin up can absorb a magnon, while changing its spin from up to down and an electron with spin down can emit a magnon, thereby changing into an electron with spin up. With the right materials and at sufficiently low temperatures, therefore, there is

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[1] Nobel Prize 2007: Press Release: 9 October 2007, The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2007 jointly to Albert Fert, Unité Mixte de Physique CNRS/THALES, Université Paris-Sud, Orsay, France, and Peter Grünberg, Forschungszentrum Jülich, Germany, ***"for the discovery of Giant Magnetoresistance".***

[2] Issued US Patents: Y. Korenblit and B. Tankhilevich, US Patent No.:7,430,074, ”Generation of terahertz waves” (2008); US Patent No.:7,440,178, ”Tunable generation of terahertz radiation” (2008); US Patent No.:7,471,449, ”Method and apparatus for generating terahertz radiation with magnon gain medium and magnon mirror” (2008); US Patent No.: 7,508,578, ”Magnon laser” (2009); US Patent No.:7,706,056, ”Modulation of terahertz radiation” (2010).

an opportunity to exploit spin characteristics to induce a magnon laser effect. There are at least two types of ferromagnets in which in equilibrium state only electrons with spin “up” exist. These are: 1. ferromagnetic semiconductors, with typical Curie temperatures far lower than room temperature, e.g. europium oxide (EuO), with Tc = 69 K =-204 C; and 2. half-metals, which often have Curie temperatures higher that the room temperature (for example, the half-metal chromium dioxide ($CrO_2$) has a Curie temperature of 390 K=117 C, whereas the half-metal (CoFeAlSi) alloy has Tc = 1100 K = 827 C). The electrons of these half-metals are almost fully polarized at room temperature (have only spin “up”), which offers the possibility to make a THz magnon-photon laser independent of a cooling apparatus. We will focus our further discussion only on these two materials as conducive for magnon lasing effect.

As noted previously, the energy of electrons depends on their spin. Fig. 1 shows schematically the dependence of the electron energy on their momenta and spin in a ferromagnetic semiconductor like EuO.

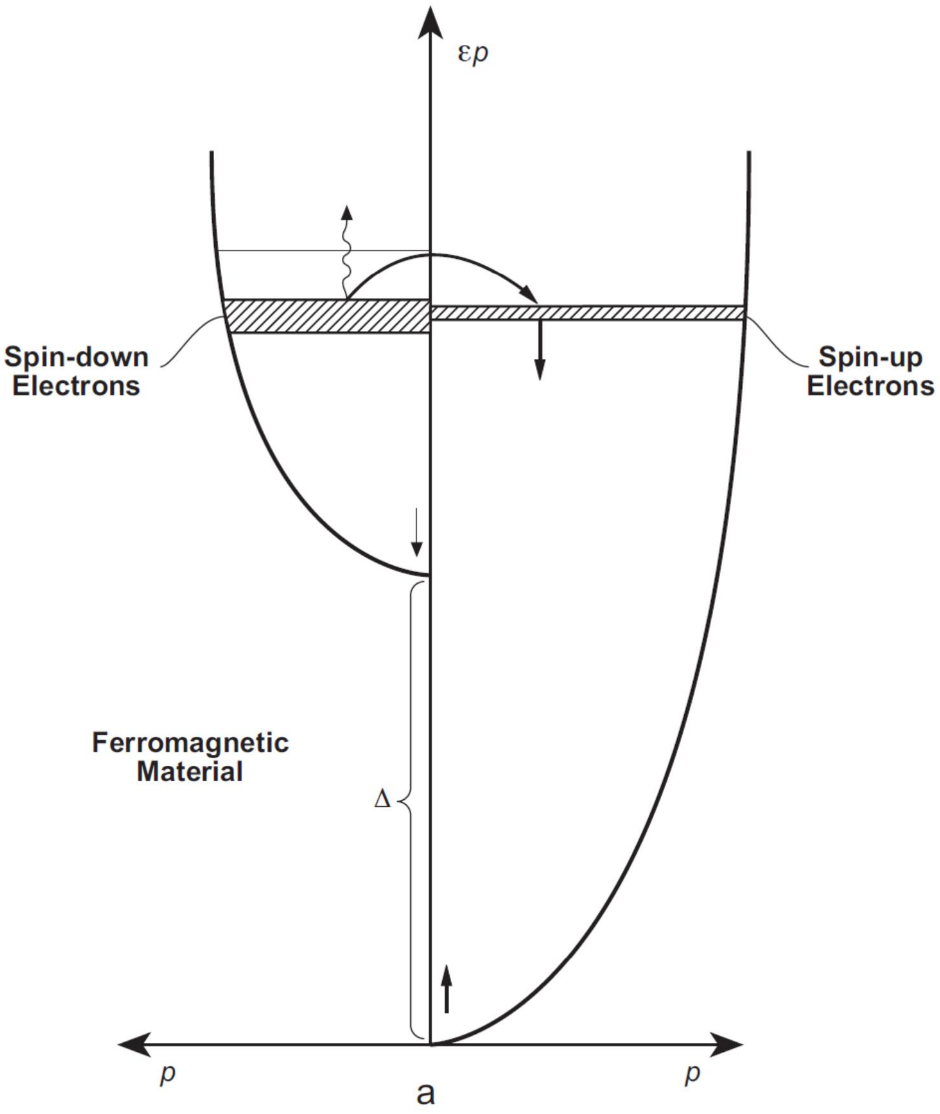

FIG. 1

The equilibrium electrons with spin up are in the lower valley, on the right, while equilibrium electrons with spin down may not populate the higher valley as the energy gap between these valleys

(6,000 K) is very large comparatively with the temperature Curie (69 K).Thus, in equilibrium, only electrons with spin up may exist.

One can, however, pump into the higher valley - either optically or with electric current - non-equilibrium electrons having spin down. These electrons will rapidly emit magnons, changing the spin from down to up, i.e. passing into high-energy states in the higher valley. The passing electrons rapidly lose their energy through the interaction, mainly with phonons and equilibrium electrons, and fall down to the bottom of the lower valley.

Thus, by pumping spin down electrons into the proper material, magnons are emitted, while the inverse process - absorption of magnons by the electrons with spin up - is substantially suppressed.

The situation resembles that in optical lasers, when photons are emitted by non-equilibrium electrons while photon absorption by the electrons is substantially suppressed. With increase of pumping of electrons with spin down in the upper valley, the number of emitted magnons also increases. Since magnons are Boson particles that, like photons, like to congregate to a particular state, magnon lasing (or an avalanche of the number of magnons in a particular state) can therefore take place at threshold electron pumping level and at certain operating temperature.

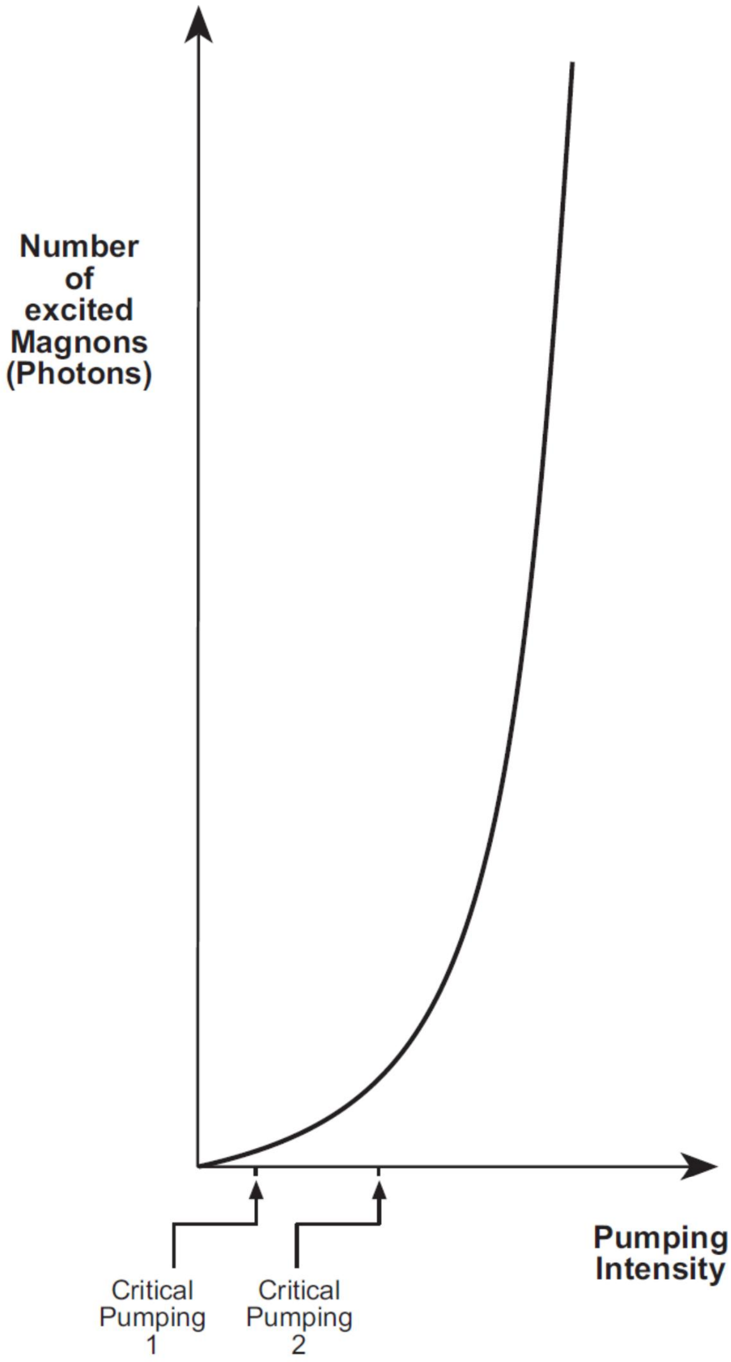
Number of excited Magnons (Photons)
Pumping Intensity
Critical Pumping 1
Critical Pumping 2

FIG. 2

The operating temperature should be far below Curie temperature if equilibrium electrons are fully or almost-fully spin polarized at the operating temperature. Our calculations show that in ferromagnetic semiconductors, a nonlinear lasing will begin at critical current pumping level 1 (as shown in FIG. 2), and an exponential lasing will begin at critical current pumping level 2 ( as shown in FIG. 2). The critical current pumping level 2 corresponds to current densities on the order of $10^4 - 10^5$ A/cm$^2$, which is the same order of magnitude as the critical currents in commonly available semiconductor-based optical lasers. These current densities, critical for exponential magnon lasing, are readily achievable in practice using our technique.

The combination of key parameters in compatible materials, such as half-metals and ferromagnetic semiconductors, is such that the frequencies of the emitted magnons lie in the THz region, with inducement of the different THz sub-regions being optimized by choosing the proper half-metal or ferromagnetic semiconductor.

### *D. Generation of photons with magnons.*

When two magnons with equal THz frequency merge, they annihilate to produce one photon with frequency twice the magnon frequency. Therefore, the Magnon Laser becomes a Terahertz Magnon-Photon Laser, with the photon stream tunable in the THz region. This process is opposite to that of generating magnons in parametric resonance, often used in magneto-electronics.

When the conditions for magnon lasing are fulfilled, the radiation power exiting from the film can reach the value of 1 $mW/cm^2$ or more. Since the frequency (or energy) of emitted magnons may be tuned by an external magnetic or electric field, the frequency (or energy) of the generated THz photons can be tuned by applying an external magnetic or electric field as well. Our calculations reveal that the frequency increases by 0.056 THz per one Tesla which is readily achievable. The frequency of the generated magnons depends also on the energy of the pumped electrons; thus the generated THz radiation may also be tuned by changing the bias.

### *E. Applications and Commercialization*

#### (i) *Medicine (cancer surgery)*

Imaging systems based on the proposed Terahertz Magnon-Photon Laser would enable real-time, image-guided cancer surgery. A Terahertz Magnon-Photon Laser imaging system should be able to obtain THz imaging of the border between the cancerous and healthy tissue, with very high spatial resolution (due to tunability) and low noise (due to high power output). A Terahertz Magnon-Photon Laser imaging system would provide a truly enabling medical tool, capable of aiding a surgeon in immediately identifying residual cancer after the main tumor has been removed, thus minimizing the need for additional surgical and other undesirable procedures.

### *(ii) Molecular imaging*

Tunable radiation in the THz frequency range enables interrogation of unique molecular vibrations. So far, applications of THz molecular imaging & spectroscopy have been limited by insufficient power and poor tunability. A THz spectrometer based on the proposed Terahertz Magnon–Photon Laser would overcome these shortcomings by generating coherent and sufficiently powerful tunable THz beams, which would make it possible to see and differentiate between very narrow resonant vibration modes. Thus, the proposed Terahertz Magnon–Photon Laser Spectrometer would enable bio sensing as a means of identifying new and different bio-molecules. This is especially important for the huge pharmaceutical market, which is estimated to be upwards of US $880 Billion (2011)[3].

### *(iii) Security applications*

On Christmas day 2009, Umar Farouk Abdulmutallab, 23, allegedly concealed in his undergarments a package containing nearly three ounces of the explosive chemical powder PETN (pentaerythritol tetranitrate). He also carried a syringe containing a liquid accelerant to detonate the explosive.

After that attempted act of terrorism, the US Transportation Security Administration ordered $165m-worth of scanners, using both

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[3] Global pharmaceutical sales are estimated to reach $880 billion for 2011, an increase of between 5% to 7% compared to 2010. The 2010 global pharmaceutical market is expected to have grown by between 4% and 5% compared to 2009. The 2011 forecast was made in a new report *IMS Market Prognosis*, by IMS Health Incorporated

millimeter and X-ray technology, from L-3 Communications. Each full body-scanner cost around $200,000.

However, the explosive device smuggled in the suspect's clothing would not have been detected by selected body-scanners, or those set to be introduced in British airports, according to The Independent [4].

Indeed, since the attack was foiled, body-scanners, using "millimeter-wave" technology (and revealing a much-feared unclothed image of a scanned passenger's body), have been touted as a solution to the problem of detecting explosive devices that are not picked up by traditional metal detectors – such as those containing liquids, chemicals or plastic explosive. But, tests by a team of scientists at QinetiQ[5] showed the millimeter-wave scanners did pick up shrapnel and heavy wax and metal, while plastics, chemicals and liquids were missed. If a material is low density, such as powder, liquid or thin plastic – or through the passenger's own clothing – the millimeter waves can pass through and the object is not shown on screen.

The proposed Terahertz Magnon-Photon Laser Scanner imaging system used to generate high power tunable THz radiation would be able to detect the sub millimeter chemical powder PETN (pentaerythritol tetranitrate) and other threatening substances.

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[4] The Independent (UK), "*Are planned airport scanners just a scam*? "; Sunday, 3 January 2010

[5] **QinetiQ** is a British global defense technology company, formed from the greater part of the former UK government agency, Defense Evaluation and Research Agency (DERA), when it was split up in June 2001 (with the smaller part becoming Dstl). Its major sites are Farnborough, Hampshire, MoD Boscombe Down, Wiltshire, and Malvern, Worcestershire where it was formerly DERA and is the largest single employer in the area. Former Central Intelligence Agency Director George Tenet served as an independent non-executive director to QinetiQ's board between October 2006 and January 2008.[1] It is listed on the London Stock Exchange and is a constituent of the FTSE 250 Index.

### *(iv) Non-Invasive Blood Glucose Monitoring System*

The proposed Terahertz Magnon-Photon Laser Scanner imaging system, when used to generate high power tunable THz radiation, will be able to detect blood sugar by tuning the generated THz frequency until a window of THz penetration in water can be reached[6] and by detecting the resonance sugar frequencies that lie in the THz region.

## *F. Conclusion*

We have shown that when spin-down electrons are pumped into ferromagnetic semiconductors or half-metals, one can achieve the conditions for magnon lasing. The dipole-type magnon-magnon interaction results in the generation of THz photons. Thus, the proposed device is a Terahertz Magnon-Photon laser. The generated frequency is material-dependent, such that by choosing the proper material, THz frequencies occupying the region from 0.1 THz to 10 THz can be obtained. The critical pumping for lasing depends on the magnon decay rate, and mainly on the exchange magnon-magnon scattering. Hence, to lower the critical pumping level required, one should work at operating temperatures much smaller than Tc. Thus, for Terahertz Magnon-Photon laser working at room temperatures half-metals having high Tc are desirable.

There exist now a large variety of half-metals with Tc higher than room temperature. For example, Co2FeSi is a half-metal with Tc = 1100 K. This offers the possibility to get intensive THz radiation at room temperature.

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[6] THz Laboratory Measurements of Atmospheric Absorption Between 6% and 52% Relative Humidity by Andriy Danylov, 2006, Submillimeter-Wave Technology Laboratory, University of Massachusetts Lowell 175 Cabot Street, Suite 130, Lowell, MA 01854

Ferromagnetic semiconductors have Tc that is lower than room temperature, and therefore they can be used as THz generators only at induced low temperatures, thereby raising expense and perhaps decreasing utility. But in such ferromagnetic semiconductors, the non-equilibrium electrons may be pumped not only by current but also by optical excitation; being near-dielectric, and unlike half-metals, ferromagnetic semiconductors do not absorb optical photons. Optical excitation could be more efficient than electric field pumping in injecting non-equilibrium electrons with spin down into higher valley of ferromagnetic semiconductors thus rendering even sub-room temperature implementations of our invention useful for certain applications.