Novel spintronic device: terahertz magnon-photon laser

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Abstract. A novel method of generating THz radiation is proposed. The method is based on pumping of non-equilibrium electrons into the upper (spin-down) subband of spin-polarized half-metallic ferromagnets or ferromagnetic semiconductors. The electrons rapidly emit magnons with THz frequency, pass into highly excited states of the spin-up subband, and fall into the ground state due to interaction with the equilibrium spin-up electrons or emitting optical phonons. The mechanism of magnon generation is similar to a three-level laser, and at a critical pumping intensive magnon lasing begins. Merging of two magnons generates a THz photon. Thus, a magnon laser becomes a THz photon laser, the generated power being of orders of milliwatt vs. several microwatt power generated by contemporary devices. The generated frequency is material dependent, and can be changed by tuning the magnetic field and the bias. The proposed device may have many applications in different fields including medicine (cancer surgery), molecular imaging, security problems etc.

1. Introduction
The THz region of the electromagnetic spectrum defined by the frequency range of 0.3 to 10 THz have recently become the subject of heightened activity in the physic and engineering communities because of promising new applications in semiconductor physics, medical, space and defence industries (for a review see [1]). As argued in the above review, the lack of a high-power, low-cost THz source is the most significant limitation of modern THz systems. In recent years some new methods were proposed for THz wave generation [2],[3],[4],[5]. However, a powerful compact tunable narrow-band source of electromagnetic THz radiation is still lacking.

In this paper a novel method of generating THz radiation, a THz magnon-photon laser is proposed, which is capable of generating narrow-band THz power of orders of milliwatt [6]. The proposed source utilizes spin-polarized ferromagnetic materials like half-metals and ferromagnetic semiconductors. In both of these materials the conduction band is split by the exchange interaction into two subbands with opposite spin orientation, and only electrons states in the lower subband ("spin up" majority electron states) are occupied at zero temperature. The exchange gap $\Delta$ is of order of hundreds meV.

Nonequilibrium electrons pumped into the upper subband ("spin down" minority electron states) rapidly emit magnons, with a large wave vector $q \approx \hbar^{-1} (2m\Delta)^{1/2}$, where $m$ is the electron effective mass. The frequency of these magnons fall into the THz region. For instance the classical ferromagnetic semiconductor EuO (Curie temperature, $T_c = 69^\circ$K) the gap is $\Delta = 0.6$ eV. With $m \approx m_0$, where $m_0$ is the free electron mass, and the magnon stiffness, $D = 10.8$ meV$\cdot$A$^{-1}$, the energy of the excited magnons is $h\omega = Dq^2 = 2.1$ meV, and the frequency $f_m = (2\pi)^{-1} \omega = 0.54$ THz. In half-metals ($T_c \geq 300$ K) $\Delta$ is the distance between the Fermi energy and the bottom of the minority carrier band, and...
it lies in the region 0.1–0.4 eV. The stiffness \( D \) is of order of 100-200 meV\( \cdot \) Å\(^2\). Thus, the frequency of the excited magnons should be several THz.

Merging of two magnons with frequency \( f \) and wave vectors \( q \) and \(-q\) generates a photon with frequency \( 2f \). This process is a process reversal to the well known process of parametric magnon generation by electromagnetic radiation. At critical pumping currents \( j_c \approx 10^4 \sim 10^5 \) Å/cm\(^2\) the magnon lasing process begins, and the device should generate high-power narrow-frequency THz radiation. The device is of nano scale and is capable of large scale productions. The device can also work at room temperature if half metals are employed.

2. Dynamics of a magnon laser

The system of equations which govern the behavior of the pumped electron, \( f_{\downarrow}(p) \), and magnon, \( N(q) \) distribution functions can be written as

\[
\frac{\partial N(q)}{\partial t} = \{1 + N(q)\} \Gamma_e(q) - \{N(q) - N_0(q)\} \Gamma_{ms}(q)
\]

\[
\frac{\partial f_{\downarrow}(p)}{\partial t} = g(\epsilon_p) - f_{\downarrow}(p) \gamma_{em}(p)
\]

Here \( g(\epsilon_p) \) is the generation function of the spin-down electrons. \( \Gamma_e(q) \) is the relaxation rate of magnons in collisions with electrons

\[
\Gamma_e(q) = 4\pi \hbar^2 \frac{I^2}{S v_0} \int d^3q (2\pi \hbar)^{-3} \delta(\epsilon_p - \hbar\omega_q - \epsilon_{p-q+}) f_{\downarrow}(p),
\]

where \( v_0 \) is the unit cell volume, and \( I \) is the s-d (s-f) exchange interaction.

\( \Gamma_{ms} \) is the relaxation rate of the magnons to the equilibrium value \( N^{(0)} \), which includes the magnon-magnon scattering, \( \Gamma_m \), scattering of magnons on the surface, and the scattering of magnons by the majority spin-up electrons. Note that in both half-metals and ferromagnetic semiconductors the last scattering is relatively small, since one-magnon processes are forbidden by the energy conservation law.

\( \gamma_{em} \) is the electron-magnon relaxation rate

\[
\gamma_{em}(p) = 4\pi \hbar^2 \frac{I^2}{S v_0} \int d^3q (2\pi \hbar)^{-3} \delta(\epsilon_p - \hbar\omega_q - \epsilon_{p-q+}) \{1 + N(q)\}.
\]

The magnon emission is described by the first term in (1). It follows from the energy conservation law that if \( \epsilon_p = p^2 / 2m \) is smaller than \( \Delta \), the wave vectors \( q \) lie in a smooth interval \( q_1 \leq q \leq q_2 \), where \( q_{1,2} = \hbar(p_0 \pm p_0 = (2m\Delta)^{1/2} \gg p) \).

After the emission of magnons the electrons pass into highly excited states of the spin-up subband. Since the ionicity in ferromagnetic semiconductors like EuO is large, the electrons in this state will most probably emit optical phonons and fall into low-energy states of this subband, see figure 1.

In half-metals this should happen due to the strong interaction of the high-energy electrons with the spin-up electrons at the Fermi surface. As a result the absorption of magnons by the spin-up electrons in the highly excited states is strongly suppressed, and the system acts as a three-level laser.
Figure 1. This figure illustrates the process of strong electron–magnon interaction (comparatively with electron-electron or with electron-phonon interaction) wherein a nonequilibrium electron put in the upper subband with spin down rapidly emits a magnon with a large wave vector.

The electron-magnon relaxation rate $\gamma_{em}$ is very large, of order $3 \cdot 10^{12} - 10^{13}$ sec$^{-1}$. Thus, after a very short time of order $\gamma_{em}^{-1}$ the electron distribution function according to (2), reaches the value

$$f_{\downarrow}(p) = g(\varepsilon_p) / (\gamma_{em}(p))^{-1}$$

(5)

It follows from this equation and (3) and (4):

$$\Gamma_e(q) = \int d^3 p \, g(\varepsilon_p) \delta(\varepsilon_p - \hbar \omega_q - \varepsilon_{p_\uparrow}) Z(p),$$

(6)

with

$$Z(p) = \int d^3 q \, \delta(\varepsilon_p - \hbar \omega_q - \varepsilon_{p_\uparrow}) (1 + N(q)).$$

(7)

These equations together with (1) give a complicated integro-differential equation for $N(q,t)$. We solve it in the limits of small and large $t$ assuming that the temperature, $T$, is low, $kT \ll \hbar \omega(q_0)$, and therefore $N(q,0) = N^{(0)}(q)$ is much smaller than unity.

Consider not too large times, when $N(q)$ is also small, $N(q) \ll 1$. Then (1) transforms into a simple differential equation

$$\partial N(q) / \partial t = \Gamma_e^*(q) - [N(q) - N^{(0)}(q)]\Gamma_m(q),$$

(8)

with $\Gamma_e^*$ given by (6), in which the functional $Z$ does not depend on $N(q)$. The solution of (8), with the initial condition $N(q,0) = N^{(0)}$, is
This solution holds only at such \( t \), when the condition \( N < 1 \) is satisfied. It is seen that if the ratio \( \Gamma^* (\Gamma_{ms})^{-1} \) is less than unity, \( N \) changes from \( N = N^{(0)} \) at \( t = 0 \) till

\[
N(q) = \Gamma^* (\Gamma_{ms})^{-1}
\]  

at \( t > (\Gamma_{ms})^{-1} \), being always small. Thus, in this case only spontaneous emission of magnons is important. In the stationary state given by (10), \( N(q) \) increases linearly with the pumping.

If \( \Gamma^* (\Gamma_{ms})^{-1} \) exceeds one, the solution of (9) is valid only at \( t \ll (\Gamma_{ms})^{-1} \), when \( N \) remains small. When \( N \) reaches a value of order unity, the stimulated emission dominates. Thus, the threshold pumping for a fast increase of \( N(q) \) caused by the stimulated emission can be written as

\[
\Gamma^* - \Gamma_{ms}
\]  

(11)

The same condition follows from the arguments borrowed from the theory of optical lasers. The larger the pumping the less is the time delay required for the stimulated emission to become dominant.

We calculate \( \Gamma^* \) for two types of pumping:

\[
g(\epsilon_p) = g_0 \delta (\epsilon - \epsilon_p).
\]

\[
g(\epsilon_p \leq \epsilon) = g_0; \quad g(\epsilon_p > \epsilon) = 0.
\]  

(12)

One obtains from (6) and (7) that \( \Gamma^* \) is the same for both types of pumping given by (12)

\[
\Gamma^* = g_0 \epsilon (4 \Delta)^{-1}.
\]  

(13)

It follows then from (11) that the threshold pumping is given by

\[
g_0 = g_{th} = 4 \Delta (\epsilon)^{-1} \Gamma_{ms}
\]  

(14)

If the pumping exceeds the above threshold, the behavior of \( N(q) \) depends on the anisotropy of the generation.

Suppose first that the generation is isotropic, and \( N(q) \) does not depend on the direction of \( q \). Then the function \( Z \) increases with the increase of the pumping in such a way, that \( g \) is always smaller than \( \Gamma_{ms} \). In other words, it is the feedback relationship between the magnon emission rate and the population of the subband with spin down (see (2)), which leads to the steady state at sufficiently large \( t \).

When the pumping exceeds \( g_{th} \) the stimulated emission of magnons becomes important, and the number of magnons increases nonlinearly with pumping. At pumping \( g_0 > g_c = \Delta^2 \epsilon^{-1/2} g_{th} \) the system is in a steady state, with \( N(q) \) increasing exponentially with pumping in a smooth range of magnon wavelengths \( q \) near \( q_1 \), wherein the range of magnon wavelength \( q \) decreases exponentially with the increase of pumping.

The \( t \)-dependence of \( N \) is quite different, if the magnon emission is anisotropic, i.e. \( N(q,t) \) increases mainly at \( q \) in the vicinity of some \( q^* \) (there may exist several such optimal vectors). Then the function \( Z \), which is an average of \( N(q,t) \), is not very sensitive to the value of \( N(q^*,t) \), and the feedback relation discussed above is not essential. Therefore, \( \Gamma^* \) can be considered as time independent even in the case, when \( N(q^*,t) \) is large. The solution of (1) is:

\[
N[q^*, t] = N^{(0)}(q^*) + (\Gamma^* (1 + N^{(0)}) (\Gamma^* - \Gamma_{ms})^{-1}) \exp (((\Gamma^* - \Gamma_{ms})t) - 1).
\]  

(15)
Thus, $N(q^*, t)$ increases exponentially with time, if $g_0$ exceeds $g_{th}$. At some time, when $N$ becomes very large the feedback may cause the system to enter into a steady state also at anisotropy conditions.

One can get strong anisotropy of the magnon emission using two magnon mirrors [6] with an active region in between. The magnon mirrors serve as a magnon resonant cavity, and when $g_0$ exceeds $g_{th}$, the magnons, which move perpendicular to the magnon mirrors, are mainly emitted, thus leading to an exponential increase of their number with time.

3. Generation of THz radiation

The interaction of magnons with electromagnetic radiation was considered in [7]. Merging of two magnons with wave vectors $q$ and $q'$ generates a photon with wave vector

$$k = q + q',$$  \hspace{1cm} (16)

and with frequency $\nu_k$ equal to

$$\omega_q + \omega_{q'} = \nu_k = c k$$  \hspace{1cm} (17)

where $c$ is the light velocity. It follows from these conservation laws that $k$ is much smaller than $q$, i.e. $q = -q'$.

The probability of transformation of two magnons in a photon is the greatest, when $q$ is along the magnetization. We consider, therefore a magnon laser, in which just these magnons are mainly generated. Then the evolution of the number of generated photons, $n(t)$, with time is given by the equation:

$$\frac{dn}{dt} = WN^2(t) \left[ n(t) + 1 \right] - Wn(t) \left[ N(t) + 1 \right] - n(t)^{-1}.$$  \hspace{1cm} (18)

Here $W$ is the photon generation probability, which is proportional to the square of the magnetization and is of order $10^7$ s$^{-1}$, $\tau_{ph}$ is the photon relaxation time. The main relaxation mechanism is the absorption of photons by the conduction electrons.

Suppose that $N(t)$ increases exponentially with time

$$N(t) \propto \exp(\beta t).$$  \hspace{1cm} (19)

Then (18) can be solved analytically in two limiting approximations.

3.1. $WN\tau_{ph} \ll 1$.

Equation (18) can be rewritten as

$$\frac{dn}{dt} + n(t)^{-1} = WN^2(t).$$  \hspace{1cm} (20)

The solution of this equation is:

$$n(t) = W t_{ph} N^2(t) (2\beta t_{ph} + 1)^{-1}.$$  \hspace{1cm} (21)

In this regime, which is realized, when $N$ is not too large, but, of course, it is much larger than unity, $n$ may be smaller than 1, if $WN^2\tau_{ph}$ is small, or larger than 1, if the opposite inequality holds.

3.2. $WN\tau_{ph} \gg 1$.

Then equation (18) transforms into

$$\frac{dn}{dt} + 2WN(t) n(t) = WN^2(t)$$  \hspace{1cm} (22)
One gets

\[ n(t) = \frac{N(t)}{2} + \text{const.} \]  \hspace{1cm} (23)

Thus, when the magnon lasing takes place, the number of generated THz photons increases exponentially with time.

### 3.3. Tunability of the generated radiation

In an external magnetic field \( H \), the spin-wave spectrum for high-frequency magnons is

\[ \hbar \omega_q = (\hbar \omega_0 + Dq^2) \]  \hspace{1cm} (24)

Here \( \hbar \omega_0 = g_L \mu_B H \), where \( g_L \) is the Lande g-factor \((g_L \approx 2)\) and \( \mu_B \) is the Bohr magneton. Hence, the frequency of the generated radiation is

\[ f = 2\omega_q/2\pi = \pi^{-1}(\omega_0 + \hbar^1Dq^2) \]  \hspace{1cm} (25)

Thus, the magnetic field-induced tunability, \( t_H \), defined as

\[ t_H = \frac{\partial f}{\partial H} \]  \hspace{1cm} (26)

is

\[ t_H = \frac{g_L \mu_B}{\pi \hbar} = 0.056 \text{THz} / T. \]  \hspace{1cm} (27)

The frequency of the radiation can be tuned also by the bias. As mentioned above, at high pumping levels, the generated magnons have wave-vectors, which are close to \( q_1 \), i.e., the frequency of the excited magnons is

\[ \omega_q = 2mD \hbar^{-2}[\Delta - (\Delta \epsilon)^{1/2}] \]  \hspace{1cm} (28)

\( \epsilon \) depends on the bias. Therefore \( \omega_q \) and, hence, the frequency of the generated radiation \( f = 2\omega_q/2\pi \) can be tuned by changing the bias.

### 3.4. Theory vs experiment

In a recent paper [8] THz generation by current induced spin injection into a Permalloy was observed. The current density was of the order of \( 10^9 \text{ A/cm}^2 \). In Permalloy, unlike half-metals discussed above, the density of states of both majority and minority electrons is finite at the Fermi surface, i.e. there is no exchange gap. Therefore, generation of radiation due to direct transitions of the injected electrons across the exchange gap, considered in [5], does not happen. It seems that the only mechanism, which can lead to THz radiation at the above experimental conditions is that, considered in this paper and in [6]. The exchange shift of the spin-up and spin-down sub-bands in Permalloy is 0.2 eV, and therefore the frequency of the excited magnons, and, hence, of the generated radiation should indeed be of order of several THz. However, since there is no exchange gap in Permalloy, there is a strong absorption of magnons by spin-up (majority) electrons, and there is no magnon lasing.

### 4. Applications and Commercialization

#### 4.1. Medicine (cancer surgery)
Imaging system based on the proposed Terahertz Magnon-Photon Laser would enable a real-time image-guided cancer surgery.

One of the first considerations of the issue of using micro millimeter to centimeter wavelengths for imaging human tissue is the tissue resolution obtainable. This is of course related to the wavelength in tissue (not in air). Thus for 30 mm wavelengths in tissue of dielectric coefficient between 30 and 60 the wavelength is about 5 mm (wavelength/√dielectric coefficient). The resolution for terahertz frequencies is 100 times less but the dielectric coefficient is expected to be also much less resulting in an expectation of effective tissue wavelengths of about 200μm. When one considers the question of the depth of interrogation that plagues optical or EM field imaging, it is important to note that the tissue linear attenuation is much less than the measured attenuation in deionized water and for 1 terahertz attenuation is less by a factor of about 5 from attenuation in the near infra-red. For terahertz frequencies we are dealing with attenuations of 100 to 120 per cm [9] which in simple terms is an attenuation of more than 10,000 1 mm thick. But the contrast between muscle and fat should be over 10:1. Thus it is not surprising to note the high contrast in transmission images of meats and foods using 0.8 terahertz frequencies from the recent work of Fitzgerald and co-workers [10]. In sum, the success with NIR reflection and transmission imaging of breast tissues in vivo has been encouraging in view of the scattering and attenuation suffered by the photons. In addition, from optics differences in tissue types will be reflected in differences in the index of refraction (square root of dielectric coefficient), thus the interfaces between tumor tissue and normal tissue in the sub millimeter range are expected to give image contrast differences.

The maximum terahertz output power from the photo mixer used in [11] was about 10 microwatt at the low-frequency end (100 GHz), just above 1 microwatt at 1 THz, and then began to fall off, thus it was not tunable at all. Thus, as compared with the THz imaging system used in [12] the proposed Terahertz Magnon-Photon Laser imaging system should be able to obtain THz imaging of the border between the cancerous and healthy tissue with much higher spatial resolution (due to tunability) and would also minimize the noise (due to high power output).

Therefore, the proposed Terahertz Magnon-Photon Laser imaging system would provide a truly enabling 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 procedures.

4.2. Molecular imaging
THz frequency range allows interrogation of unique molecular vibrations. So far applications [13] THz molecular imaging & spectroscopy have been limited by insufficient power and poor tunability of the generated THz radiation. THz Spectrometer based on the proposed Terahertz Magnon–Photon Laser would enable to overcome these shortcomings by generating almost coherent 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 means of identification different bio-molecules. This is especially important for the huge pharmaceutical market, which is estimated to be upwards of US $680 Billion (2009 estimates).

4.3. Security applications
On Christmas day 2009, Umar Farouk Abdulmutallab, 23, allegedly concealed in his underpants a package containing nearly 3oz of the chemical powder PETN (pentaerythritol tetranitrate). He also carried a syringe containing a liquid accelerator to detonate the explosive.

After that act of terrorism, the US Transportation Security Administration ordered $165m-worth of scanners, using both millimeter and X-ray technology, from L-3 Communications. Each full body-scanner costs around $200,000.

However, the explosive device smuggled in the clothing of the Detroit bomb suspect would not have been detected by body-scanners set to be introduced in British airports according to The Independent [14].
Indeed, since the attack was foiled, body-scanners, using "millimeter-wave" technology and revealing a naked image of a passenger, 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 scientists in the team at Qinetiq showed the millimeter-wave scanners picked up shrapnel and heavy wax and metal, but plastic, chemicals and liquids were missed. If a material is low density, such as powder, liquid or thin plastic – as well as the passenger's clothing – the millimeter waves 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) used in the recent terrorist act.

5. 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 generating of THz photons. Thus, the proposed devise is a magnon-photon laser. The generated frequency is material dependent and choosing the proper material, THz frequencies occupying the whole THz region from 0.1 THz to 10 THz can be obtained. The critical pumping for lasing depends on the magnon decay, mainly on the exchange magnon-magnon scattering. Hence, to lower the critical pumping, one should work at temperatures much smaller than Tc. Another reason to lower the temperature is the need to use ferromagnets with highly polarized electrons.

There exists now a large variety of half-metals with Tc higher than the room temperature. E.g., Co2FeSi is a half-metal with Tc = 1100 K [15]. This offers the possibility to get intensive THz radiation at room temperature. In ferromagnetic semiconductors Tc is smaller than the room temperature, and therefore they can be used as THz generators only at low temperatures. But in semiconductors the non-equilibrium electrons may be pumped not only by current but also by optical excitation. The last method would reduce the absorption of the radiation by the electrons and increase, therefore, the efficiency of the device.
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