Subwavelength terahertz spin-flip laser based on a magnetic point-contact array

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We present a theoretical design for a single-mode, truly subwavelength terahertz disk laser based on a nanocomposite gain medium comprising an array of normal-metal/ferromagnetic (FM) point contacts embedded in a thin dielectric layer. Stimulated emission of light occurs due to spin-flip relaxation of spin-polarized electrons injected from the FM side of the contacts. Ultrahigh electrical current densities in the contacts and a dielectric material with a large refractive index, neither condition being achievable in conventional semiconductor media, enables the thresholds of lasing to be overcome for the lowest-order modes of the disk, making single-mode operation possible. © 2011 Optical Society of America

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The prospect of combining electronics and photonics on a single chip by integrating lasers with electronic devices in high-density integrated circuits is an exciting one. This would, however, require the on-chip lasers to be small and operate in the submillimeter range of wavelengths, which corresponds to the terahertz (THz) frequencies normally associated with vacuum tube and solid-state electronic oscillators (300 GHz to 10 THz). Nevertheless, for such relatively low frequencies (compared to optical microcavity lasers) it has already been possible to design disk lasers with diameters, $2a$, somewhat smaller than the emission wavelength λ, with $2a/\lambda = 0.7$ for the smallest disks [1,2]. This was achieved by cascading more than 200 quantum wells in a semiconductor disk, which led to a gain of $g = 27\,\mathrm{cm}^{-1}$ and made it possible to overcome the lasing threshold for the mode with azimuthal index $m = 5$. However, a further miniaturization of laser devices employing dielectric resonators hits a limit. This is because of the relatively low gain that can be achieved with typical active media such as semiconductors, dyes in polymer matrices, and ion-doped crystalline materials.

In this Letter, we propose to use a novel active medium to solve this problem. The idea is to use a nanocomposite material (see Fig. 1) in which an ensemble of nanobridges (point contacts) protruding from a metal surface and embedded in a thin dielectric with a large refractive index make contact with a ferromagnetic (FM) layer to form a disk-shaped resonator. We envisage a situation in which the electrons in the magnetic material are predominantly in the spin-up state, while spin-up electrons in the nonmagnetic metal have a higher energy than spin-down electrons due to Zeeman splitting caused by an external magnetic field. Therefore, if a bias voltage is applied across the resonator in such a way that electrons are injected from the magnetic layer into the metallic point contacts, the majority of electrons would flow into the upper Zeeman level. If the pumping current of spin-polarized electrons is large enough, a population inversion will therefore be created in the point contacts. Subsequent electron energy relaxation through spin-flip transitions associated with photon emission can result in gain for electromagnetic radiation [3,4]. The great advantage in using point contacts is that if the contact diameter is of the order of 10 nm, then electrical current densities as high as $10^9\ \mathrm{A/cm^2}$—which would melt a bulk metal—can be achieved [5], creating a very efficient pump source.

Electron spin-flips affect the magneto-resistance of the point contact and have been predicted to give rise to a characteristic peak in the resistance for a magnetic field that corresponds to resonant stimulated emission of photons by electrons, a prediction that has been confirmed by recent experiments on a single point contact [4,6]. Modeling shows that the experimental peak height corresponds to an optical gain in the point contact of $g_{\mathrm{pc}} \sim 10\text{–}100\,\mathrm{cm}^{-1}$ [6], which demonstrates that the irradiated single point contact is an optically active medium with extremely high optical gain [7]. We suggest that an ensemble of such point contacts, embedded in a suitable dielectric material, could be used as the active medium in lasing devices.

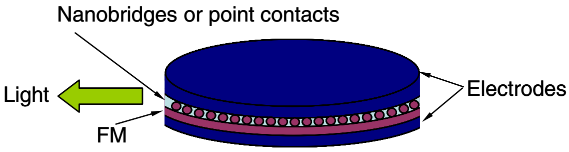

Fig. 1. (Color online) Sketch of the proposed subwavelength disk laser, which is based on a novel nanocomposite active material comprising an ensemble of point contacts protruding from a nonmagnetic metal (upper electrode), embedded in a thin dielectric layer and making contact with an FM metal disc.

Relaxation of the electrical injection current leads to Joule heating of the point contact, but, on the other hand, the electron flow carries heat away from the contact. To avoid overheating, small point contacts of $d{\sim}10\,\mathrm{nm}$ are needed, with area density of $n \sim (10d)^{-2}$. In this case, the average optical gain, $g = 0.1g_{\mathrm{pc}}$, can be estimated to be of order 1–10 cm^{-1}, depending on the voltage applied to the point contact [8]. For an active region (the point-contact core) made of a normal metal and subjected to a magnetic field of the order of 10 T, the frequency of the emitted light is approximately 0.3 THz, which is at the low-frequency limit of the THz range [9]. For FM point contacts [7], the expected frequency range is determined by the exchange spin splitting in the material, typically 1–30 THz, and can be controlled by changing the composition of the ferromagnet and thereby its Curie temperature.

We propose to build a THz laser as a thin multilayered disk whose central layer is a 10–20 nm dielectric sandwiched between normal metal and FM slabs connected by nanobridges (Fig. 1). Such a metal–dielectric disk is an open resonator for which the disk diameter determines the working-mode type and hence the wavelength of the emitted light. Off the disk plane, electromagnetic field confinement is provided by metallization of the faces of the disk; in the disk plane confinement is due to the different refractive indices of the inner and outer materials.

It is convenient to study the lasing modes, including their wavelengths, thresholds, and field patterns, as a lasing eigenvalue problem (LEP), where Maxwell's equations are solved with appropriate boundary conditions on the disk surface and the outgoing radiation condition at infinity. Full details of this newly developed approach and its application to various microlasers can be found in [10,11]. The LEP eigenvalues are pairs of real numbers corresponding to the lasing frequency (or wavenumber, k) of the mode and the threshold value of material gain γ (the imaginary part of the refractive index in the active region) required for lasing. The average optical gain per unit length, g, is connected to the material gain as $g = k\gamma$.

For the considered nanocomposite disk whose top and bottom faces are metallic and whose thickness is a fraction of the wavelength, a useful approximation can be obtained if one assumes the metallic faces to be perfect conductors. Then, the lasing modes can be viewed as TE-type modes in a two-dimensional circular dielectric, uniformly active resonator. In this case, for each azimuthal order m, the LEP is reduced to a characteristic equation given, e.g., by Eq. (29) in [11]. Results of the LEP analysis for such a model of a disk resonator filled with material of refractive index $\alpha = 3.6$ (i.e., the same as in [2]) are shown in Fig. 2, where discrete LEP solutions are shown as points in the plane $(2a/\lambda, \gamma)$. Note that, while the thresholds obtained in this way correctly account for the radiation losses, they neglect the losses in the conductors. Hence, the total losses are underestimated, which should be more important for higher-order modes.

As the refractive index varies from 1.5 to 10, Fig. 3 shows that the characteristic frequencies of the lower-order E-type modes of the disk, E_{01} and E_{11}, decrease and vary from $2a/\lambda \sim 0.5$ to 0.02. The E_{01} mode is of particular interest since the electric field has a maximum in the center of the disk. However, because of its field pattern, its threshold gain is considerably higher than for the other modes, including the E_{11} mode. As shown in Fig. 3, a laser operating on the E_{11} mode needs to overcome a threshold gain ranging from 0.4 to 0.2 if the refractive index varies between 1.5 and 5. These values appear realistic for the proposed composite medium, where the material gain depends both on the voltage bias applied to the point contacts [8] and on the density of point contacts.

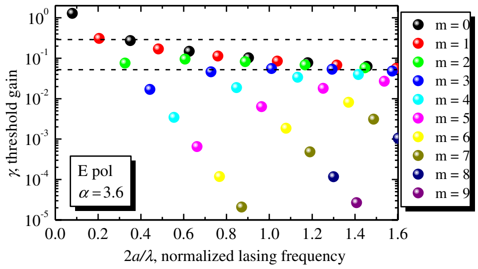

Fig. 2. (Color online) Set of lasing frequencies and threshold gains for TE_{mn} modes in a disk with bulk refractive index $\alpha = 3.6$. For a given azimuthal index m, the radial index n takes the values 1, 2, 3, from left to right. The upper dashed line indicates a gain of $\gamma = 0.3$ ($g = 160\,\mathrm{cm}^{-1}$ at 3 THz), which can be achieved with the proposed nanocomposite medium for a particular frequency if the magnetic field is tuned to give resonant spin-flip photon generation. The lower dashed line at $\gamma = 0.043$ corresponds to $g = 27\,\mathrm{cm}^{-1}$ achieved at the same frequency in [2].

It should be noted that existing semiconductor microdisk lasers, which use whispering-gallery modes at optical and THz frequencies, are multimode devices. Several modes get into the emission range of the active material and compete with each other. Working in one of the lower-order modes makes laser operation more stable because the distance in λ to the nearest mode is larger. As the emission wavelength is controlled by the applied magnetic field, tuning to a particular mode is achieved by the selection of disk radius and the level of pumping, where the latter determines whether the threshold value of material gain is overcome. Note that the thresholds for the lower modes are less sensitive to the precise shape of the disk boundary. Hence, the manufacturing tolerances can be relaxed.

Unlike semiconductor microdisk lasers, the proposed laser can use novel dielectric materials with very high refractive indices, ranging from 5 ($\mathrm{HfO_2}$) to the "colossal"

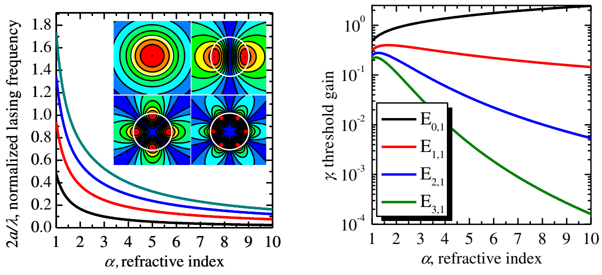

Fig. 3. (Color online) Normalized lasing frequencies (left panel) and threshold gains (right panel) for the E_{01}, E_{11}, E_{21}, and E_{31} modes plotted as a function of the resonator refractive index α. Insets show the field patterns of the different modes when $\alpha = 3.0$.

value of 50, and reasonably low losses [12]. As simulations show (see Fig. 3), if $\alpha = 5$ or larger, then even the modes E_{21} and E_{31} demonstrate field confinement along the rim of the disk with correspondingly low thresholds, while the cavity size is deep inside the subwavelength range ($2a/\lambda < 0.3$).

Furthermore, small-size cavities working on the lower-order modes have a small number of lobes in the far-field radiation patterns. This is more convenient than many identical beams typical for the whispering-gallery modes. The near-field patterns for the four lowest modes in the disk resonator are shown as insets in the left panel of Fig. 3.

Finally, we describe how the proposed laser device can be fabricated by using colloidal lithography [13,14]. This technique has been successfully used to make nanoparticle arrays for applications in various areas of science and technology. Typically, a suitable buffer/bottom electrode layer is coated with a monolayer of polystyrene particles by, e.g., spinning a polystyrene colloidal fluid containing a ~1% aqueous solution of polystyrene particles. Under suitable conditions, the result is a close-packed monolayer of particles, with diameters from 40 to 300 nm, which uniformly cover the bottom electrode. The diameter of the particles can be decreased to the 10 nm range and the separation between particles can be increased by reactive ion etching in a mixture of O_2 and CF_4. This fabrication step offers flexibility in selecting the point contact size and the array density. The surface can then be covered by a thin insulating layer and polystyrene particles subsequently removed by acetone. The resulting mesh with nanosize holes is covered by a metal layer acting as the top electrode, and suitable contacts are arranged to the top and bottom metal layers. The in-plane size and shape of the point-contact array is defined by lithographically patterning the top and bottom electrodes. This process, which provides a robust and relatively inexpensive way to produce large arrays of extremely small particles, is currently employed by the authors to produce a spin-laser demonstrator that will be reported elsewhere.

In conclusion, we have proposed a new design principle for a single-mode, truly subwavelength THz disk laser, which is based on using an active medium that enables the material gain to be several orders of magnitude higher than if conventional semiconductor media are used. This is because the proposed nanocomposite active medium contains an array of metal-FM nanobridges from which light is emitted, as a high-density spin-polarized current relaxes by emission of photons when the electrons flip their spin in "vertical" transitions between Zeeman-split energy levels.

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7. If photons are emitted from a FM rather than a nonmagnetic point contact, it was shown in [3] that the exchange field can increase the optical gain by a factor $(c/v_F)^2$ to approach 10^5–10^6 cm^{-1}. Indications of photon emission from FM metal junctions have been reported [15].
8. The optical gain in a point contact of the type proposed is $g_{\rm pc} = g_0 V/V^*$, where $g_0 = 3\pi^2 n_0 \mu B^2 \omega/\varepsilon_F v_F$, ε_F and v_F are the normal metal Fermi energy and Fermi velocity, n_0 is the electron density, μB is the Bohr magneton, ω is the radiation frequency, V is the applied voltage, and $eV^* \sim h\omega/2\pi$ [4].
9. For fields in the range 0.1–10 T, the device would act as a maser and emit microwaves in the range 3–300 GHz.
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