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Bosonic lasers: The state of the art

(Review Article)

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Bosonic lasers represent a new generation of coherent light sources. In contrast to conventional, fermionic, lasers they do not require inversion of electronic population and do not rely on the stimulated emission of radiation. Bosonic lasers are based on the spontaneous emission of light by condensates of bosonic quasi-particles. The first realization of bosonic lasers has been reported in semiconductor microcavities where bosonic condensates of exciton-polaritons first studied several decades ago by K.B. Tolpygo can be formed under optical or electronic pumping. In this paper we overview the recent progress in the research area of polaritonics, address the perspective of realization of polariton devices: from bosonic cascade lasers to spin transistors and switches.

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78.45.+h Stimulated emission;
71.35.–y Excitons and related phenomena;
42.50.Ar Photon statistics and coherence theory.

Keywords: polariton, lasing, Bose–Einstein condensation, vortices.

Contents

1. Introduction

Our modern digital society is largely built on optoelectronic devices. Infrared lasers pulse optical data through a global network of silica optical fibres; light-emitting diodes illuminate our homes and backlight liquid-crystal displays in our phones, tablets and televisions; visible lasers store and read data in DVDs; photovoltaic cells harvest clean energy direct from the sun. Every one of these technologies has been made possible by advances and paradigm shifts in the physics of semiconductor materials and devices. The double heterostructure gave co-confinement of carriers and light to reduce diode laser thresholds to a practical level. The growth of quantum wells (and later quantum dots) has enabled unprecedented flexibility to engineer electronic energy states and transitions. Current optoelectronic technologies exploit these advances to manipulate separately the semiconductor charge carriers and light. We believe that the next paradigm shift will not control these separately but will couple together the photon and electron in a bosonic state called a “polariton”. Polaritons are quasiparticles that arise from strong coupling between light and matter, typically in a semiconductor optical microcavity (Fig. 1). They have hybrid properties of photons and excitons, combining the mobility and flexibility of light, with the possibility of interactions due to the matter component. Their physics is quite different from the physics of fermionic electrons and holes in a semiconductor, on which current optoelectronic devices are based. At high enough densities, or low enough temperatures, polaritons can form a macroscopic coherent quantum state, a polariton condensate, or a polariton laser. Such a coherent state shows much of the same physics as Bose–Einstein condensation, as has been seen for cold atoms, but without requiring the ultra-low temperatures needed for atoms.

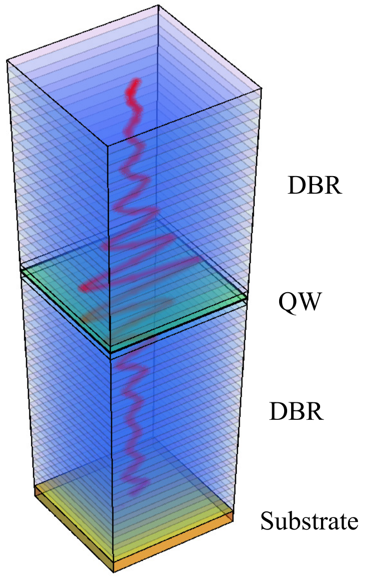

Fig. 1. (Color online) Schematic of a microcavity. A pair of distributed Bragg reflectors (DBRs) form an optical cavity, which enhances the interaction of light with a quantum well at the center of the cavity. The electric field amplitude of a confined mode is illustrated in red.

2. Concept of polariton lasing

LASER stands for Light Amplification by Stimulated Emission of Radiation. The amplification of light takes place in electronic systems where stimulated emission exceeds absorption [1]. This condition cannot be fulfilled at thermal equilibrium: it requires the inversion of electronic population, i.e., a negative temperature. To invert its electronic population the system needs external pumping of energy above some critical value, referred to as “lasing threshold”. Nowadays, the term “laser” is applied to any device producing coherent, monochromatic and unidirectional light [2]. It turns out that stimulated emission of radiation is not the only way to generate laser light. In bosonic lasers, light is emitted spontaneously by a condensate of particles accumulated in a single quantum state [3]. Bosonic lasers do not require negative temperatures: they may even operate at thermal equilibrium. They still need pumping, but, theoretically, can have zero thresholds.

Which particles are good for forming condensates able to emit light? Bosonic condensates of atoms have been realized at extremely low temperatures [4], and the condensed atoms are usually in their ground state, incapable of emitting light. This makes atomic condensates impractical for the generation of light (the term “atom laser” refers to a coherent flow of atoms, not of photons [4]). On the other hand, condensates of mixed light-matter quasiparticles, exciton-polaritons, emit light very well [3]. These condensates may be realized in semiconductor microcavities at relatively high temperatures, even at room temperature. This is why exciton-polariton lasers (polariton lasers) are most likely to become the first commercialized bosonic lasers.

The seminal 1992 paper by Weisbuch, Nishioka, Ishikawa and Arakawa [5] reporting the observation of a strong exciton–photon coupling in semiconductor microcavities opened to a wide scientific community the world of exciton-polaritons: mixed light-matter quasiparticles with very peculiar properties. More than a decade afterward, the first unambiguous experimental observation of the Bose–Einstein condensation (BEC) of exciton polaritons in microcavities was reported using a CdTe-based microcavity [6]*. Soon after, two other groups reported the BEC of exciton-polaritons in GaAs-based microcavities

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[*] Earlier works reported the stimulation of polariton photoluminescence [7] and the onset of second order coherence [8], but not simultaneously with the key features of spontaneous spatial coherence and polarization.

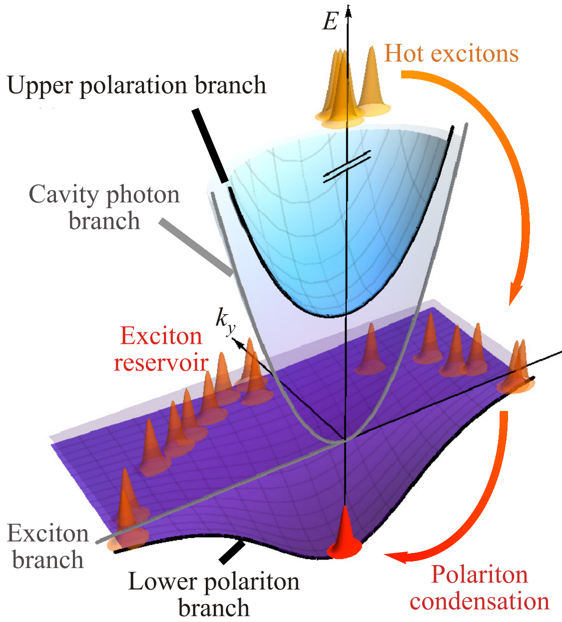

Fig. 2. (Color online) Polariton dispersion and schematic of polariton condensation. Exciton and cavity photon modes couple to generate two new dispersion branches: the upper and lower polariton branches. Hot excitons injected at high-energies relax their energies, through states with high in-plane wavevector, before undergoing stimulated scattering to the lowest energy state. The macroscopic buildup of polaritons in a low-energy state forms a polariton condensate.

[9,10]. In a polariton laser, the microcavity is excited nonresonantly, either optically or electronically. A gas of electrons and holes created in the cavity forms excitons, which subsequently thermalize amongst themselves, mainly through exciton–exciton interactions.

Their kinetic energy is lowered by interactions with phonons [11,12] or excitons [13] and they relax along the lower polariton dispersion branch (see Fig. 2). They finally scatter to their lowest energy state, where they accumulate because of stimulated scattering. The coherence of the condensate therefore builds up from an incoherent equilibrium reservoir and a BEC phase transition takes place. The condensates of exciton-polaritons emit light which tunnels through the Bragg mirrors. This emission is spontaneous, however, the light going out has all the properties of a laser light: it is coherent, monochromatic, polarized and unidirectional. The spontaneous emission of radiation by mixed light-matter condensates constitutes the polariton lasing effect.

3. Realization of polariton lasers in semiconductor microcavities

Polariton lasers with optical pumping have been realized in GaAs, CdTe and GaN [14,15] based planar, pillar [16,17], and photonic crystal [18] microcavities. They represent the first class of optoelectronic devices based on exciton-polaritons and possess unique characteristics including ultra-low threshold power, controllable polarization of emission, and peculiar statistics of emitted photons. Room temperature operation has been demonstrated in GaN and ZnO-based polariton lasers [19–21].

While a majority of research has been focused on semiconductor-based systems, significant advances have also been made in the development of organic based systems, where polariton BEC was reported [22,23] and the spatial coherence of room temperature polariton lasers demonstrated [24].

4. Polariton lasers with electrical injection

Recently, polariton lasers with electrical injection of carriers have been realized (see Fig. 3) [25]. This technological breakthrough opens the way to a new generation of optoelectronic devices based on the Bose–Einstein condensates of mixed light-matter quasiparticles. It has further been demonstrated that electrical contacts can be used to switch polariton lasers [26].

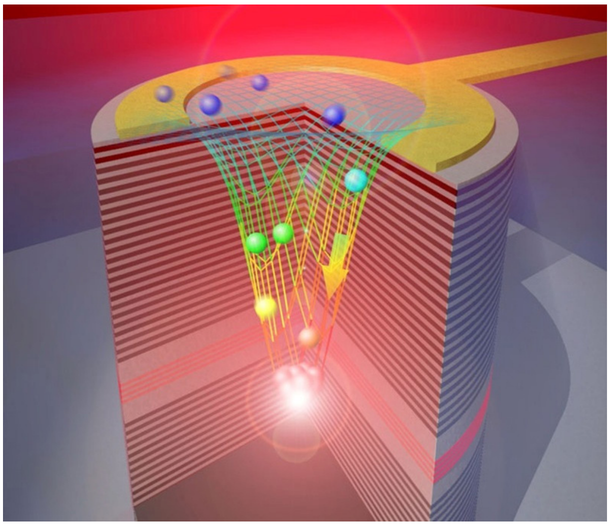

Fig. 3. (Color online) Diagram of the electrically driven polariton laser. Electrically injected electrons and holes attract each other which results in the formation of excitons: hydrogen-like quasiparticles, which emit and reabsorb light inside the microcavity. This leads to the formation of exciton-polaritons, quasiparticles which spend a part of their time as photons and another part as excitons. The exciton-polaritons accumulate in a single quantum state called a condensate, which spontaneously emits light going away by tunneling through the mirrors. (Graphics: Arash Rahimi-Iman, Department of Applied Physics, University of Wrzburg), adapted from http://www.uni-wuerzburg.de/en/sonstiges/meldungen/detail/artikel/eine-neue-1/

5. Spatial dynamics of polariton lasing structures

A key characteristic of polariton condensates and lasers is their spatial coherence [27], which develops spontaneously and spreads both in time and spatially across the microcavity plane [28]. The coherence also spreads and synchronizes across regions in the presence of disorder [29]. The resulting coherent state of polaritons is well described by a nonlinear Schrödinger equation (also known as a Gross–Pitaevskii equation), modified to account for gain and loss in the system [30]. Theoretical studies revealed that this equation supports a variety of spatially nontrivial structures, including: vortices and vortex lattices [31,32]; solitons [33–37]; and various other patterns [38–40].

5.1. Vortices

Experimentally, one of the first examples of nontrivial spatial structures of polariton BECs was the observation of quantized vortices [41,42]. In principle vortices can form out of phase fluctuations during the formation of the polariton condensate (i.e., the Kibble–Zürek mechanism). In practice, the observation of vortices at well defined positions, after averaging over multiple laser shots, implies that disorder in the system also plays an important role in pinning vortex paths [43,44] (see also Fig. 4). In addition, polariton condensates, being two-dimensional, can also exhibit a Berezinskii–Kosterlitz–Thouless (BKT) transition [45], characterized by the binding of vortex–antivortex pairs. Indeed this effect is challenging to distinguish as disorder tends to make microcavities spatially inhomogeneous. Still experiments using spatially inhomogeneous pumping have successfully demonstrated the formation of vortex–antivortex pairs [46].

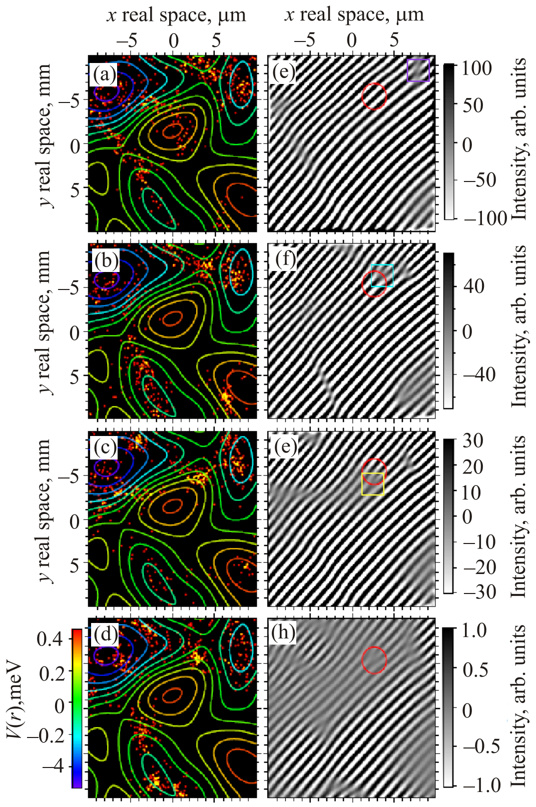

Fig. 4. (Color online) Dynamics of vortices in a polariton condensate under pulsed excitation, simulated from the driven-dissipative Gross–Pitaevskii equation. (a)–(d) Shot-integrated locations of vortices at subsequent time frames (40, 50, 60 and 90 ps) and contours of a disorder potential. The vortices can be seen to preferentially form near local minima of the potential. (e)–(h) Corresponding shot-integrated interference patterns, which are comparable to experimental measurements. Figure reproduced from [43].

5.2. Trapping and condensation in structured potentials

Spatially structured excitation of planar microcavities has been considered by several groups, allowing the trapping of polariton condensates in optically controlled potentials [47,48]. Chiral trapping potentials can also be engineered to generate vortices [49]. Experiments with Mexican hat shaped profiles showed how it was possible to trap vortex–antivortex pairs [50]. The optical trapping of polaritons can also be achieved based on the balances between optically controlled gain and loss [51], providing a mechanism for dissipative solitons [33].

Aside optically induced potentials, polaritons can also be confined growing structures of reduced dimensionality, such as microwires [52] and micropillars [16] that can lead to the condensation of polaritons in artificial photonic molecules [53].

Several works have also focused on the formation of polariton condensates in periodic potentials [10,54,55]. Here interesting effects include the condensation into solitonic gap states [56], weak lasing [57], and the stochastic condensation at different symmetry points in the reciprocal lattice [58], which could be relevant for an exciton-polariton analogue of valleytronics.

5.3. Pattern formation

In addition to the potential to form vortex lattices [31], polariton condensates and lasers can form a variety of other spatial patterns. Expanding condensates were shown to lead to "sunflower ripples" [59]. Ring-shaped optical excitation has also been shown to allow the spontaneous formation of patterns [60], which can be interpreted as a modulational instability. An example simulation of such a situation from the driven-dissipative Gross–Pitaevskii equation is shown in Fig. 5.

5.4. Bistability and polariton condensate memories

Resonantly excited microcavities, which rely on the coherence of an external laser, are well-known for demonstrating polariton bistability [61] and multistability [62–64]. This can lead to very long-lived optical memory elements, given by the duration of application of a control laser [65], and switches [66,67] for optical circuits. To

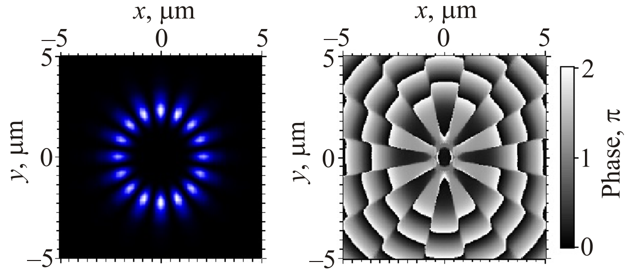

Fig. 5. (Color online) Polariton stationary state under continuous-wave ring-shaped excitation, simulated from the driven-dissipative Gross–Pitaevskii equation. Left: The polariton density breaks up into a series of lobes. Right: Corresponding polariton phase distribution in space. The figure has been adapted from [44].

interface such devices with electronics, one ideally aims to construct mechanisms of bistability based on non-resonant/incoherent excitation.

Here, a few options are available. First, using long-lifetime cavities and ring-shaped excitation it was shown that polaritons can form stochastically in one of two orbital angular momentum states [68], representing a stable persistent current [69]. Theoretically, taking orbital angular momentum states as a basis, one can consider the copying and inversion of binary information in a lattice [70].

Alternatively, the difference in polariton linewidths for different linear polarizations (transverse-electric and transverse-magnetic) was shown experimentally and theoretically to lead to a form of bistability between spin-polarized states [71]. Mechanisms of electrically controlled bistability were also demonstrated [72] and several theoretical mechanisms of bistability with incoherent excitation remain open [40,73,74].

5.5. Polariton condensate transistors and optical circuits

Several works have considered the control of propagating polariton condensates in incoherently controlled interferometers [75] and condensate transistors [76,77] (see also Fig. 6). We will review these configurations, comparing to their resonantly excited counterparts [78].

6. Bosonic cascade lasers

The realization of efficient terahertz (THz) radiation sources and detectors is one of the important objectives of modern applied physics. THz emitters and detectors are very promising for applications in biology, medicine, security and non-destructive in-depth imaging [81]. Also, wireless data transfer using THz radiation is likely to provide a higher transfer rate for indoor short distance or high altitude communication (propagation of THz radiation in the atmosphere is limited by water vapor absorption) [82]. For these multiple applications, the creation of cheap, reliable, scalable, and portable THz radiation sources and detectors

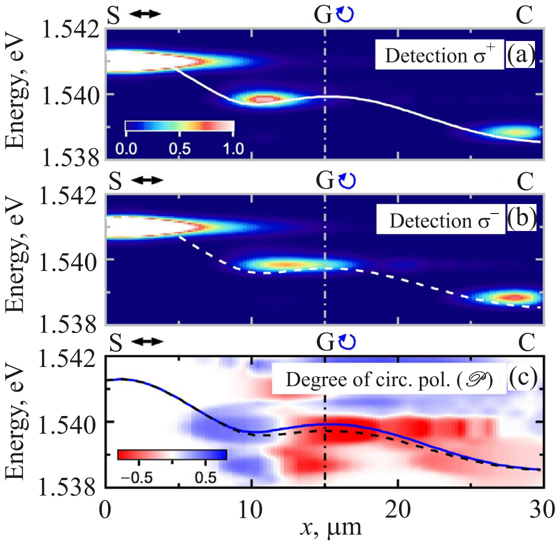

Fig. 6. (Color online) Spatially resolved spectrum of a polariton condensate spin transistor, calculated from a driven-dissipative Gross–Pitaevskii equation with energy relaxation [79]. Polaritons are injected incoherently from a source S, with a linear polarization. A circularly polarized gate G creates a barrier in the polariton potential (white curve), which partially inhibits the propagation of polaritons with the same circular polarization (a), while allowing those of opposite polarization to propagate (b) to the collector region C. (c) Degree of circular polarization. The figure is reproduced from [80].

is extremely important. None of the existing THz emitters universally satisfies the application requirements. For example, emitters based on nonlinear-optical frequency down-conversion, gas THz lasers, vacuum tubes and systems based on short-pulse spectroscopy are bulky, expensive, and power consuming. Various semiconductor devices based on intersubband optical transitions are compact but have a limited wavelength tunability range, low quantum efficiency, and require cryogenic cooling. Among the factors which limit the efficiency of semiconductor THz sources is the short lifetime of the electronic states involved (typically, fractions of a nanosecond) compared to the time for spontaneous emission of a THz photon (typically a few milliseconds). The methods of reducing this mismatch include the use of the Purcell effect in THz cavities [83] and/or the cascade effect in quantum cascade lasers (QCL) [84]. Nevertheless, until now QCLs in the spectral region about 1THz remain costly and short-lived and still show quantum efficiencies of less than 1%. Moreover, so far, there are no commercially available, reliable, compact, and cheap detectors of THz radiation which are in a great need for Information and Communication Technology (ICT) applications.

Recently novel approaches to THz generation have been formulated, solving the problem of the lifetime mismatch by exploiting polariton–polariton scattering, that allows to increase the emission rate through stimulation of the final state polaritonic population [85–89]. Some of the basic concepts on which these proposals are based are presently being tested experimentally.

In bosonic cascade lasers (BCLs) excitons or exciton-polaritons are resonantly injected into one of the upper quantum confined states in a parabolic potential trap [90], whose frequency lies in the THz region (see Fig. 7). Examples of potential experimental realizations of bosonic cascades are shown in Fig. 8. In the original scheme for bosonic cascades, excitons, being neutral particles, can not directly emit THz photons by falling from one level to the next. Still the harmonic confining potential, being different for electrons and holes, couples the internal and center-of-mass degrees of freedom of the exciton, allowing for the radiative cascade depicted in Fig. 7, in which a THz photon is emitted each time an exciton falls down a step of the harmonic ladder. This relaxation process would be stimulated by the occupation numbers of the quantum states which are subsequently visited by relaxing excitons. According to the estimations of Ref. 40, one can realistically expect 7–8 THz photons to be emitted per exciton (or exciton-polariton) injected into the system, which results in a quantum efficiency of several hundred per cent. BCLs would be a valuable alternative to fermionic QCLs as, in principle, they do not require a THz cavity, may be assembled in matrices, and are expected to be easily tunable in a wide spectral range by external electric/magnetic field [26,91,92] or by tuning the depth of the optical parabolic trap. Terahertz cavities, would however further increase efficiency by double bosonic stimulation [93]. Furthermore, it might be possible that condensates at certain steps of the cascade are formed in non-classical states characterized by photon superbunching.

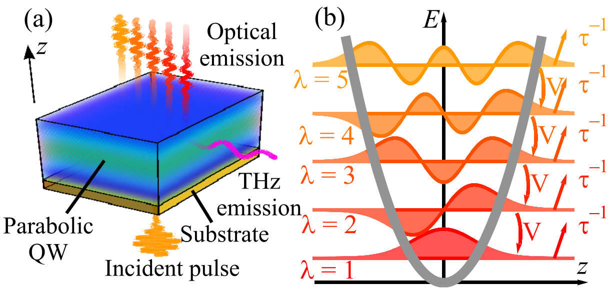

Fig. 7. (Color online) Illustration of a bosonic cascade. (a) Structure schematic: a parabolic quantum well is excited with an optical pulse and emits light at a range of frequencies. (b) Energy level diagram: the parabolic trapping potential engineers equidistant energy levels and transitions occur between neighboring levels with transition element V. Bosons in each level can decay radiatively, with characteristic decay time τ.

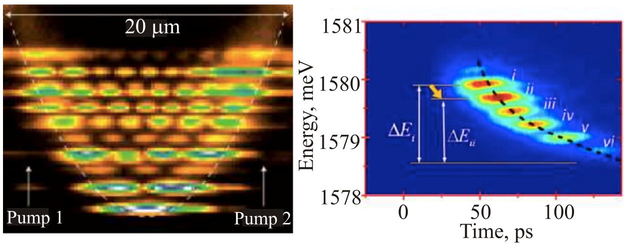

Fig. 8. (Color online) Examples of bosonic cascades. Left: Equidistant polariton condensates in a parabolic trap observed by near-field photoluminescence in a planar GaAs-based microcavity. The image is adapted from [94]. Right: Time resolved relaxation dynamics of a polariton condensate in a cascade of quantum confined states of a one-dimensional trap realized in a polariton microwire (a long and narrow stripe etched from a GaAs-based planar microcavity). The image is adapted from [95].

7. Conclusions

Over the past decade, polaritonics has made a huge step forward, and expanded from a purely fundamental research field into an interdisciplinary research area with very promising applications in solid state lighting, information processing, medicine, renewable energy, etc. The most significant progress has been achieved in the realization of polariton lasers: the first realization of the bosonic lasing concept proposed in 1996 [3].

In terms of practical applications, polariton lasers still need to find their niche. Their undoubted advantage over conventional lasers is in the significantly lower threshold power, as convincingly demonstrated by [25,96]. On the other hand, polariton condensates are fragile: they disentangle as soon as you pump a bit stronger. This is why polariton lasers are not good for high-power operations. On the other hand, bosonic condensates of exciton-polaritons may be manipulated by applying external electric and magnetic fields and by external laser beams.

The polarization and intensity of light emitted by polariton lasers can be switched from one value to another within several tens of picoseconds [65–67,97]. This high controllability of the most essential characteristics of emitted light make polariton lasers most promising for applications in optical integrated circuits and at the interface between electronic devices and optical communication lines.

Another application area which remains to be explored is the stimulation of terahertz frequency generation by polariton condensates. Given a high demand for compact and reliable sources of coherent terahertz radiation, bosonic cascade lasers based on excitons or exciton-polaritons would offer a valuable alternative to quantum cascade lasers based on electronic transitions in semiconductor superlattices. Potentially, they could operate at room temperature, emit terahertz light in the vertical direction (normal to the plane of the structure) and be as small as any vertical cavity surface emitting semiconductor laser.

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