

willem vos switching

Inloggen

Patenten

Voorbeeld bekijken ▾

Aan mijn bibliotheek toevoegen ☐

Recensie schrijven

Engels

Frans

Stand van de techniek zoeken

Deze patentaanvraag bespreken

Pdf weergeven

PDF downloaden

☐ ▾

Photonic crystal switch

WO 2003025661 A1

SAMENVATTING

The present invention provides a method and a device for changing at least locally the density of states of a photonic composite material (1), by supplying radiation energy (5), which changes the refractive index of at least one of the materials of the composite material (1). The method allows very fast switching of band gaps, and hence of transmission and other optical properties of such photonic composite materials. For example controlled emission and capturing of single photons, or transport thereof becomes possible, through excitation of impurities (4) with a band gap energy, and subsequent shifting of said band gap through supply of radiation energy.

Publicatienummer	WO2003025661 A1
Publicatietype	Aanvraag
Aanvraagnummer	PCT/NL2001/000747
Publicatiedatum	27 maart 2003
Aanvraagdatum	10 okt 2001
Prioriteitsdatum	19 sept 2001
Uitvinders	Willem Lambertus Vos , Albert Femius Koenderink , Patrick Michael Johnson
Aanvrager	Univ Amsterdam , Nog 4 meer »
Citatie exporteren	BiBTeX , EndNote , RefMan
Patentcitaties (2) , Niet-patentcitaties (4) , Vervijzingen naar dit patent (1) , Classificaties (10) , Juridische gebeurtenissen (6)	
Externe links: Patentscope , Espacenet	

BESCHRIJVING

Photonic crystal switch

The present invention relates in a first aspect thereof to a method of at least locally modifying a photonic density of states of a photonic composite structure comprising at least two materials with different refractive indices. In an article "Liquid-Crystal Photonic-Band-Gap materials: The Tunable Electromagnetic Vacuum" by Busch and John, in Physical Review Letters (1999), vol. 83, no. 5, p. 967-970, a method is disclosed wherein the three-dimensional photonic band gap of an inverse opal photonic-band-gap crystal filled with nematic molecules can be tuned by applying an electric field which rotates the axis of the nematic molecules relative to the inverse opal backbone.

A drawback of this method is that this modifying technique is relatively slow. The time scale on which the photonic band gap may be modified is of the order of milliseconds/microseconds. This is due to the relative slow response of the nematic (liquid) crystals. This slow response limits the practical usefulness of devices based on this technique.

The present invention aims at providing a method of the above- mentioned type which is substantially faster as to the modification of the photonic density of states. It is to be noted that the usefulness of this technique not only holds for the photonic band gap, i.e. a range of frequencies with substantially zero photonic density of states. It is also useful for frequency ranges with nonzero but modifiable density of states. According to the invention the method comprises the step of supplying to the photonic composite structure an amount of radiation energy for interacting with said photonic composite structure whereby the refractive index of at least one of said materials is changed in response to said amount of radiation energy. Because the response of the photonic composite structure to said radiation energy is of the order or microseconds down to femtoseconds, the very much faster modification of the density of states is obtained. This modification is due to the mentioned change of the refractive index of at least one of the materials of the photonic composite structure. This change of refractive index may be effected through a number of possible mechanisms, which will be elucidated below, but it is essential that they are much faster, i.e. faster than on a microsecond timescale. Another advantage is that no additional material is introduced in the photonic crystal that reduces the width of the photonic band gap. Hence the usefulness of the the

CLAIMS (1)

1. Claims
 1. Method of at least locally modifying a photonic density of states of a photonic composite structure (1) comprising at least two materials (2,3) with different refractive indices, the method comprising the step of supplying to said photonic composite structure (1) an amount of radiation energy (5) which is able to interact with said photonic composite structure (1) , whereby the refractive index of at least one of said materials is changed in response to said amount of radiation energy (5) .
 2. Method according to claim 1, characterised in that the radiation energy (5) is acoustic energy.
 3. Method according to claim 1, characterised in that the radiation energy (5) is electromagnetic energy.
 4. Method according to claim 3, characterised in that the electromagnetic energy is supplied in the form of laser energy.
 5. Method according to any of the preceding claims, characterised in that radiation energy (5) is supplied to substantially the whole photonic composite structure (1) .
 6. Method according to any of the preceding claims, characterised in that the radiation energy (5) is supplied from at least two different directions.
 7. Method according to any of the preceding claims, characterised in that the photonic density of states is changed by at least a factor of 2, for at least one range of frequencies.
 8. Method according to any of the preceding claims, characterised in that the photonic density of states is changed by at least a factor of 5, for at least one range of frequencies.

photonic crystal is not reduced.

In the context of this application, a photonic composite structure, also called a photonic crystal, is a composite of alternating different dielectric materials. The lattice spacing is preferably of the order 0.1 to 10 Dm, that is, of the wavelength of light (infrared, visible, ultraviolet), although other lattice spacings are not excluded. The photonic density of states (density of states for electromagnetic radiation) in such a crystal differs markedly from the photonic density of states in a homogeneous dielectric material. In the latter, the density of states as a function of frequency is substantially a parabola. In a photonic crystal, the density of states is different, with preferably, but not necessarily a range of frequencies with substantially zero density of states, and a different range of frequencies with density of states considerably higher than a homogeneous dielectric crystal.

The density of states is fundamental to a wide range of phenomena, such as spontaneous emission or dispersion forces, such as the van der Waals' Force. More rigorously, for spontaneous emission, it is the local density of states at the spatial position of the emitter that determines the rate of emission. The total density of states may be obtained by summing the local density of states, which has been normalized per volume, over all spatial positions in that volume, e.g. a unit cell. In a preferred method according to the invention, the radiation energy is acoustic energy. Acoustic energy is meant here to include optical phonons. The acoustic energy causes the material in the lattice to be locally contracted or expanded. In regions of contraction the material's refractive index is raised, in regions of expansion the refractive index is reduced. In a periodic material, acoustic vibrations may also change the lattice spacing which is another means of changing the density of states. In another preferred method according to the invention, the radiation energy comprises electromagnetic energy. Electromagnetic energy is here meant to include light (infrared, visible and/or ultraviolet) although microwaves, radiowaves etc. are not excluded. Electromagnetic energy radiation is especially advantageous because the sources thereof are very easily controlled. Furthermore, due to the small wave length of e.g. visible light, it is possible to supply said radiation energy very locally.

In principle, other means of excitation such as the use of electrochemical or electronic induced charge are possible. Often, however, they have a much slower response, and so may be of limited usefulness.

Advantageously, the electromagnetic energy is supplied in the form of laser energy. Laser energy shows the above-mentioned advantages (controllable power, supplying energy very locally) even more markedly. E.g. many laser sources exist which are pulsed, which means that energy is supplied in the form of pulses. However, the means to supply electromagnetic radiation energy is not limited to lasers. Incandescent lamps, gas discharge lamps, LED's or any other source of electromagnetic radiation may be used. It is to be noted, however, that the efficacy of the method depends on the intensity of the supplied radiation.

In the method, it is believed that the supplied electromagnetic radiation excites a plasma of free carriers, nearly free carriers or excitons in the material. Such a plasma may be generated in any dielectric. The presence of free carriers, and the number thereof, characterized by the plasma frequency, influences the refractive index of the material. A higher number of free carriers generally decreases the refractive index. This influences in turn the density of states of the material. This will be further elucidated in the description of the Figures.

It is believed possible to make use of another, related phenomenon, viz. the optical Kerr-effect. When electromagnetic energy with sufficient power density is supplied to a suitable material, the material may become polarized, which implies a change of the refractive index. The timescale of this effect is of the order of femtoseconds to picoseconds. However, the refractive index change

9. Method according to any of the preceding claims, characterised in that said photonic composite structure (1) comprises at least one range of frequencies with a substantially zero photonic density of states, which is modified by supplying said amount of radiation energy (5).

10. Method according to any of the preceding claims, characterised in that the method further comprises the step of supplying at least one additional photon (6) having a photon energy for which the photonic density of states is changed by at least a factor of 2 with respect to the corresponding photonic density of states before supplying the radiation energy (5), due to said supplying of radiation energy (5).

11. Method according to any of the preceding claims, characterised in that the method further comprises the step of supplying first additional radiation energy (5) to the photonic composite structure

(1) during a predetermined period of time, such that for at least one range of frequencies for which the photonic density of states has been modified by supplying radiation energy (5), the photonic density of states remains changed by at least a factor of 2, during at least said predetermined period of time.

12. Method according to any of the preceding claims, characterised in that the method further comprises the step of supplying second additional radiation energy (5) to the photonic composite structure (1), such that for at least one range of frequencies for which the photonic density of states has been modified by supplying radiation energy (5), the photonic density of states is changed by with at least a factor of 2.

13. Method according to any of the preceding claims, characterised in that the photonic composite structure (5) comprises a semiconducting material.

14. Method according to any of the preceding claims, characterised in that the photonic composite structure (1) comprises a first material selected from the group of solids and liquids, and a second material selected from the group of solids, liquids, gases and vacuum.

15. Method according to any of the preceding claims, in which the materials of the photonic composite structure (1) are arranged in a substantially periodic lattice structure.

16. Method according to claim 15, characterised in that the lattice structure is a cubic lattice structure.

17. Method according to claim 16, characterised in that the lattice structure is a face-centred cubic lattice structure.

18. Device comprising a photonic composite structure (1) comprising at least two materials (2,3) with different refractive indices, and first modifier means for supplying an amount of radiation energy (5) which is selected to interact with said photonic composite structure (1), to thereby modify at least locally the photonic density of states for at least a range of frequencies in response to said amount of radiation energy (5).

achievable to date is a factor of about 20 lower than that for the free carrier induced change. Furthermore, the high degree of multi-photon absorption limits the usefulness to very small volumes.

In a preferred embodiment of the method according to the invention radiation energy is supplied to substantially the whole photonic composite structure. In this way it is possible to influence the whole of a photonic composite structure with one supply of radiation energy. This may be useful to reset any possible light sources within the photonic composite structure at substantially the same time. This will be elucidated hereinbelow. Still, however, it is alternatively possible to modify the photonic density of states only locally.

In a favourable method according to the invention, the radiation energy is supplied from at least two different directions. This allows the radiation energy to be supplied more homogeneously. Effects of excitation and absorption are spread evenly over the crystal. Favourably, the two or more directions are mutually perpendicular. If for example a cubic photonic composite structure is used, the radiation may be supplied from all six faces of the cube. This ensures optimum homogeneity. Preferably, the frequency of the supplied radiation is at least equal to the frequency that corresponds to the electronic band gap energy of either of the materials that compose the photonic crystal. More preferably, the frequency of the supplied radiation is larger than the frequency that corresponds to the electronic band gap energy of either of the materials that compose the photonic crystal. This allows a large penetration depth of the radiation into the material of the crystal. In an alternative embodiment, the free carrier plasma is excited by a multiphoton process, driven by a frequency that is larger than the electronic band gap energy divided by the number of photons in the process.

Advantageously, the frequency of the supplied radiation is higher than the highest frequency of the photonic band gap of the crystal. This ensures that the supplied radiation penetrates even better and more homogeneously into the crystal. If no band gap exists in the photonic crystal, band gap should be replaced by energy range for which the photonic density of states is lower than the homogeneous dielectric case. If more than one band gap exists, it is preferred to select the band gap with the highest energy and thus frequency.

Optimally, the frequencies of the frequency range where the density of states is modified with respect to the homogeneous dielectric behavior, i.e. has a peak, a low or a gap, are between about 1.5-2 times the so-called plasma frequency of the free carrier plasma. With these frequencies, and with moderate free carrier densities, a relative large change in refractive index may be obtained in combination with minimal induced absorption. Here it is assumed that the induced absorption depends on an increase of the imaginary part of the refractive index.

In a preferred embodiment of the method according to the invention, the photonic density of states is changed by at least a factor of two, for at least one range of frequencies. "Change" comprises increase and decrease. Although any change in the photonic density of states could be used, for example for signal detection, a change by at least a factor of two is very useful because such a large change allows for example the design of logic circuitry. Such a modification of a density of states may be obtained for various ranges of frequencies, however, modification of a "band gap" is preferred. A "band gap" is meant to be a range of frequencies for which the photonic density of states is substantially zero.

In an even more favourable method according to the invention the photonic density of states is changed by a factor of at least 5, more advantageously at least 10, even more advantageously at least 100, for at least one range of frequencies. When the change in photonic density of states becomes larger, the effect on e.g. the optical properties of a photonic crystal becomes larger, such as the change in the probability that an excited emitter inside the photonic crystal will spontaneously emit a photon. This will be further illustrated in the description of the Figures.

In a preferred method according to the invention, the photonic composite structure comprises at least one range of

19. Device according to claim 18, characterised in that the first modifier means are designed to supply acoustic energy.

20. Device according to claim 19, characterised in that the first modifier means are designed to supply electromagnetic energy (5) .

21. Device according to claim 20, characterised in that the first modifier means comprise a laser.

22. Device according to any of claims 18-21, characterised in that said photonic composite structure (1) comprises at least one range of frequencies with a substantially zero photonic density of states, that can be modified by said amount of radiation energy (5) .

23. Device according to any of claims 18-22, characterised in that the device further comprises probe means for supplying one or more photons (6) having photon frequencies within a range of frequencies of which the photonic density of states is modifiable by the radiation energy (5) .

24. Device according to any of claims 18-23, characterised in that the device further comprises second modifier means for supplying first additional radiation energy (5) to said photonic composite structure (1) , selected to keep the photonic density of states for a range of frequencies changed by at least a factor of 2 with respect to the photonic density of states without said first additional radiation energy (5) being supplied.

25. Device according to any of claims 18-24, characterised in that the device further comprises third modifier means for supplying second additional radiation energy (5) , selected to change the photonic density of states for a range of frequencies by at least a factor of 2 with respect to the photonic density of states without said second additional radiation energy (5) being supplied.

26. Device according any of claims 18-25, characterised in that said photonic composite structure (1) has a substantially cubic lattice structure.

27. Device according to claim 26, characterised in that said photonic composite structure (1) has a substantially face-centred cubic lattice structure.

28. Device according to any of claims 18-27, characterised in that said photonic composite structure (1) comprises, within a body comprising a first dielectric material (2) , a substantially periodic structure of spaces comprising a second dielectric material (2) .

29. Device according to any of claims 18-28, characterised in that at least one of the materials (2,3) has been doped with impurities (4) .

frequencies with a substantially zero photonic density of states, which is modified by supplying the amount of radiation energy. Although theoretically the range of frequencies for which the photonic density of states may be modified is not subject to any particular limitation, it is preferred to comprise a band gap. Generally, the effects of modifying the photonic density of states in a band gap are larger than the changes when modifying a non-zero density of states, when supplying a certain amount of radiation energy. In other words, it is easier to obtain a large relative change in the density of states at frequencies inside the band gap. This modification of a band gap may be obtained by at least three different mechanisms: the band gap may be removed, i.e. the density of states becomes non-zero for every frequency. - the band gap is narrowed, i.e. the range of frequencies for which the density of states is substantially zero is decreased. the band gap is frequency shifted, i.e. the range of frequencies for which the density of states is substantially zero is shifted along the frequency axis.

Obviously, a combination of these three mechanisms may also occur.

It is to be noted here that an absolute zero density of states is theoretically only obtainable in an infinite and perfect crystal. If in a range of frequencies the photonic density of states would actually be zero, spontaneous emission for these frequencies is impossible, and an excited particle with an emission frequency in this range would stay excited forever. In a real crystal the density of states will always be non-zero. However, as long as the density of states is substantially lower than the homogeneous density of states by at least a factor of 5 it is said to be substantially zero in the context of this application. Here the homogeneous density of states is defined as the density of states in a homogeneous dielectric material with a dielectric constant equal to the volume averaged dielectric constants of the materials in the photonic crystal.

Furthermore, a photonic crystal necessarily also possesses frequency ranges for which the photonic density of states is increased. If the number of wave vectors, i.e. directions, is limited, then the spontaneous emitted radiation is channeled into these directions and may cause stimulated emission. This will be elucidated below.

Advantageously, the method further comprises the step of supplying at least one additional photon having a photon frequency for which the photonic density of states is changed by at least a factor of 2 with respect to the corresponding photonic density of states before supplying the radiation energy, due to said supplying of radiation energy. These one or more photons may be used to represent information. Said photons may be confined to a cavity inside the photonic composite structure. When the photonic density of states is changed by at least a factor of 2, the probability of the light escaping the cavity again also changes by roughly a same factor. Alternatively, the additional photon may be emitted by an excited particle, be it an impurity or a part of the composite structure itself. When such a particle is brought in an excited state, and subsequently the photonic density of states is changed, the probability of the particle emitting the photon also changes by said factor of at least 2. As discussed above, such a factor of at least 2 allows the design of logical circuitry. A factor of at least 5, advantageously at least 10, even more advantageously at least 100 allows more design flexibility, larger signal differences and a larger gamut of possible applications. Throughout the application, such graduated factors would cause similarly graduated advantages. For clarity, they will be repeated no more.

In an advantageous embodiment of the method according to the invention, the method further comprises the step of supplying first additional radiation energy to the photonic composite structure during a predetermined period of time, such that for at least one range of frequencies for which the photonic density of states has been modified by supplying radiation energy, the photonic density of states remains decreased by at least a factor of 2, during at least said predetermined period of time. Ordinarily, when the radiation energy is supplied, the free electrons are excited on the very fast time scale, of the order of femtoseconds. Hence, the switching, or to be more precise, the rise time of the switching will be ultrafast. The duration of the excited state, with lowered refractive index and modified density of state, after the supplying of radiation energy has stopped, is determined by the relaxation time of the free carriers. This depends on the nature of the material, e.g. semiconductor and on the degree of disorder therein. The relaxation time can range from picoseconds in amorphous Si, via nanoseconds in pure GaAs to microseconds in pure crystalline Si and Ge. Hence, at a certain point in time during the relaxation the magnitude of the modification will fall below a value below which the desired effect disappears. This point in time may however be shifted by supplying said first additional radiation energy. By thus supplying first additional energy the free carrier density, and thus the modification of the density of states, is kept at at least the desired level. In the case where the modification of the density of states is obtained through other effects, e.g. the mentioned optical Kerr-effect, then also this modification may be kept at the desired level by supplying additional radiation energy.

Although it is possible to supply radiation energy continuously for as long as the effect is desired, it is also possible to supply said first additional radiation energy intermittently. Care should be taken that the next amount of first additional radiation energy is supplied before the desired effect falls below a predetermined threshold value. It may be contemplated to use different sources of energy for the radiation energy and the first additional radiation energy. For example a very powerful laser may be used for supplying the radiation energy, while a much less powerful (pulsed) laser may be used for supplying the first additional energy.

A possible advantage of using said maintained state with modified photonic density of states is e.g. the "locking up" of

photons. Thereto it is for example possible to send a photon into the photonic composite structure having a band gap. The photon frequency is selected to lie outside this band gap. Then radiation energy is supplied to the photonic composite structure, whereby the band gap is modified such that said photon frequency falls within the band gap after supplying the radiation energy. In other words, the photonic density of states for the photon frequency is decreased, favourably by as large a factor as possible. This means that the probability of the photon escaping from the crystal or a cavity in the crystal again, either by transmission or by reemission, is also decreased by roughly the same factor. If this factor is very large, e.g. 100, the photon is effectively "caged". As long as the photonic density of states remains decreased, it cannot escape from the crystal.

Another possible use, without being limited thereto, is the changing of the photon emission properties of an excited particle, be it an impurity inside or a part of the composite structure itself, with an emission frequency inside the band gap. When the photonic density of states is increased from substantially zero to a finite value, it becomes possible for the particle to emit a photon. Alternatively, when the emission frequency is outside the band gap in a region of high density of states and it is changed to substantially zero, it becomes impossible for the particle to emit a photon. It is important to note that the local photonic density of states at the position of the particle should become substantially zero, or at least be modified substantially. Another possible use, without being limited thereto, is the changing of the optical transmission properties of the photonic composite structure. When the photonic density of states is lowered to substantially zero, it becomes impossible for the photon to travel through the crystal in any direction. Hence, a photon trying to enter the crystal will be reflected, and a photon inside the crystal will be localised or confined. It is important to note that the total photonic density of states should become substantially zero, or at least be modified substantially. If e.g. a one-dimensional photonic crystal or a photonic crystal with a Bragg stop gap for only one crystal axis is considered, any blocking of the photon would only occur in one direction, viz. the axis parallel to the relevant reciprocal lattice vector. Such a one-dimensional photonic crystal would block photons travelling along said axis, but would freely transmit photons travelling at least slightly off axis. Hence, such a crystal is very sensitive as to correct alignment, and can furthermore only be used in one direction.

In a preferred method according to the invention, it further comprises the step of supplying second additional radiation energy to the photonic composite structure, such that for at least one range of frequencies for which the photonic density of states has been modified by supplying radiation energy, the photonic density of states is changed with at least a factor of 2. By supplying said second additional radiation energy, or at least the correct amount thereof, it is possible to modify the photonic density of states further. In this way it is possible that e.g. a band gap or at least a range of frequencies with lowered density of states, is "shifted" to still another range of frequencies. This means that at a particular frequency for which the photonic density of states has been decreased, increased, respectively, by supplying radiation energy, the density of states is increased, decreased, respectively, after supplying said second additional radiation energy. In the case of a decrease to substantially zero density of states, this might be called the opening and closing of the band gap respectively.

An advantage of the above-mentioned method is as follows. By supplying radiation energy, the photonic density of states is modified on a very fast time scale. However, the relaxation of the plasma and hence of the photon density of states to the ground state occurs on a very much slower time scale. By supplying said second additional radiation energy, one no longer depends on this relaxation, since the extra modification by said second additional radiation energy may be applied after a predetermined time interval. When one considers the example of first opening a band gap by supplying radiation energy, the band gap may be closed again by supplying said second additional radiation energy. For then the band gap is shifted to even higher frequencies. This allows not only the very fast switching on, but also the very fast switching off of a photonic device through switching of the photonic density of states, with a predetermined time interval.

In an advanced embodiment, the radiation energy may be supplied in more than one portion at predetermined time intervals, such that the photon density of states is changed in a sequence of more than one step. This allows a band gap to be opened at different predetermined times for additional photons with different frequencies.

In another advanced embodiment, the second additional radiation energy may be supplied in more than one portion at predetermined time intervals, such that the photon density of states is changed in more than one step. This allows a band gap to be closed at different predetermined times for additional photons with different frequencies.

In a preferred method according to the invention, the photonic composite structure comprises a semiconducting material. In a semiconducting material it is very easy to excite a plasma of free carriers through supplying radiation energy. Moreover, because of their wide spread use in the "chips" industry, they are very easily handled and processed. Many examples of semiconducting materials are known to the person skilled in the art. However, other materials such as insulators may also be used, insulators being nothing more than semiconducting materials with a (very) high electronic band gap energy. Due to this higher electronic band gap energy, it is however more difficult to excite said plasma.

In an advantageous embodiment of the method according to the invention, the photonic composite structure comprises a first material selected from the group of solids and liquids and a second material selected from the group of solids, liquids, gases and vacuum. For the purpose of the application, vacuum is treated as a material here. When the first and the second material are selected as described above, it becomes possible to make a photonic composite structure. By

appropriately alternating said second and first material, a crystal with a photonic density of states substantially different from a homogeneous density of states may be fabricated. The first and the second material should be inert with respect to each other, i.e. they should not react chemically, or dissolve in one another. When two liquids are used, they should not be mutually miscible, but the one should form a pattern of liquid globules in the other liquid. When a combination of liquid and gas is used, the gas should form a pattern of bubbles in the liquid. Of course the combination of liquid and vacuum is to be excluded. Examples of suitable materials will be discussed hereinbelow.

Advantageously, the materials of the photonic composite structure are arranged in a substantially periodic lattice structure. With a substantially periodic lattice structure, the modifications of the local photonic density of states with respect to the homogeneous density of states are the same for symmetry-related equivalent points throughout the whole crystal, as opposed to a structure which is not periodic. However, features like a lowered photonic density of states may still occur in a non-periodic lattice structure. The expression "substantially" periodic means that there are large parts in the lattice structure that show little or no irregularities such as vacancies or interstitial particles. Obviously, a real crystal can never be absolutely periodic because it is finite. Furthermore, it is very difficult to prevent said crystal defects completely. However a small number of defects will have little influence on the total photonic density of states. In an advanced embodiment of the method, intentional defects are made in the photonic crystal, where the crystal symmetry significantly deviates locally from the substantially periodic structure. Point defects such as single vacancies may act as cavities with a high quality factor for frequencies in the band gap. Line defects may act as waveguides for frequencies in the band gap. A defect can have a strong effect on the local density of states.

In a preferred embodiment of the method, the lattice structure is a cubic lattice structure. Because of the high spatial symmetry the likeliness of a photonic density of states showing e.g. a band gap is much higher than with other lattice structures. More advantageously, the lattice structure is a face-centered cubic lattice structure. Here, the diamond structure is to be included, since it consists of two interpenetrating face-centered cubic lattices, displaced along the body diagonal of a cubic cell by one quarter of the length of a diagonal. Of all the cubic lattice structures the diamond structure shows the widest frequency range of substantially zero density of states and thus the largest possibility of the photonic density of states with the desired characteristics, i.e. lowered density of states, or even substantially zero density of states for certain frequency ranges .

The invention also relates to a device comprising a photonic composite structure comprising at least two materials with different refractive indices, and first modifier means for supplying an amount of radiation energy which is selected to interact with said photonic composite structure, to thereby modify at least locally the photonic density of states for at least a range of frequencies in response to said amount of radiation energy. Such a device is suitable to carry out the method according to the invention. A system of two separate entities, i.e. a photonic crystal and a means to supply radiation energy, co-operating functionally is also contemplated.

In a preferred embodiment of the device, the first modifier means are designed to supply acoustic energy. Such first modifier means may be embodied as vibrator means with a very high vibrating frequency, including optical means. The vibrator means cause the photonic composite structure to vibrate with the same frequency. As explained above, the vibration causes the refractive index to vary. The high frequency is needed to ensure that the variation of the refractive index occurs on a sufficiently fast time scale of the order of microseconds or faster.

In another preferred embodiment of the device according to the invention, the first modifier means are designed to supply electromagnetic energy. The electromagnetic energy may be selected from the group of radiowaves, microwaves, light, either infrared, visible or ultraviolet. Electromagnetic energy has the advantage that it is very easily controlled.

Preferably, the first modifier means comprise a laser. A laser is a very convenient source of electromagnetic energy. A laser emits a very controlled beam of electromagnetic radiation. Very high power densities are achievable, and also very many possible frequencies. Advantageously the laser is a pulsed laser, which allows a very fine control of the supplied quantity of energy during a well-determined short time. Possible laser sources comprise Ti-Saf lasers, and semiconductor lasers such as VCSELs .

In a preferred embodiment of the device according to the invention, the photonic composite structure comprises at least one range of frequencies with a substantially zero photonic density of states, that can be modified by the amount of radiation energy. A "band gap" or range of frequencies with a substantially zero photonic density of states is particularly useful because here the photonic density of states is very sensitive to modification through supplying radiation energy. A range of frequencies with a substantially peaked photonic density of states is also particularly useful because here the photonic density of states is very sensitive to modification through supplying radiation energy. Hence, large effects may be obtained even when supplying limited amounts of energy. However, even photonic composite structures without one or more band gaps may be used.

Advantageously, the device further comprises probe means for supplying one or more photons having photon frequencies within a range of frequencies of which a photonic density of states is modifiable by the radiation energy. With such a device, it is possible to supply additional photons, which may represent information or energy, which photons may be

controlled through the modifiable photonic composite structure. As described above, it is possible to "lock up" photons or influence them otherwise by supplying radiation energy to the photonic crystal. Obviously, when use is made of a certain range of photon frequencies, the photonic density of states within this range of frequencies should be modifiable by supplying radiation energy. Even without probe means, the device may be useful. E.g. it may serve as a switchable omnidirectional lightblocker. In a way, the source of the blocked light could be called a probe means here as well, although they do not necessarily form part of the device itself. Transmission of radiation with photon frequencies inside the band gap is not possible. Thus switching of the band gap switches the transmission properties, in all directions at the same time.

In a preferred embodiment of the device according to the invention, the device further comprises second modifier means for supplying first additional radiation energy to said photonic composite structure, selected to keep the photonic density of states for a range of frequencies changed by at least a factor of 2 with respect to the photonic density of states without said first additional radiation energy being supplied. The second modifier means allow for the photonic density of states being kept at a certain value to counteract the effects of relaxation of the free carrier plasma.

The second modifier means may comprise a source of first additional radiation energy similar to the source of radiation energy described above. It may however be different. E.g. the source of radiation energy may be a pulsed laser, whereas the second modifier means may comprise a continuous laser, or a high pressure mercury discharge lamp. Other combinations are possible as well.

Although it is advantageous to maintain the photonic density of states at a decreased level it is also possible to keep it at an increased level. This is e.g. the case when one considers a ground state band gap. When the band gap is "shifted" to higher frequencies, the photonic density of states inside the original i.e. ground state band gap is increased. And it will remain increased as long as the second modifier means keep supplying the first additional radiation energy.

Preferably, the device further comprises third modifier means for supplying second additional radiation energy, selected to change the photonic density of states for a range of frequencies by at least a factor of 2 with respect to the photonic density of states without said second additional radiation energy being supplied. With this device it is possible to modify the photonic density of states in addition to the first modifier means and the second modifier means. As described above, ordinarily when no more radiation energy is supplied, the free carrier plasma in the photonic composite structure will relax and the photonic density of states will return to its ground state. E.g. when a band gap has been "shifted" to a different range of frequencies one could say that a band gap is opened for said second range of frequencies. By having the third modifier means supply second additional radiation energy, the band gap may be shifted to yet another range of frequencies. Hereby the band gap for the modified range of frequencies is closed again, not because of relaxation but because of active second shifting of the band gap. This allows switching within a desired time, not being limited to the relaxation time.

In an advanced embodiment, at least one of the group of first modifier means, second modifier means, and third modifier means is designed to supply radiation energy in more than one portion at predetermined time intervals, such that the photon density of states is changed in a sequence of more than one step. This allows a band gap to be opened at different predetermined times for additional photons with different frequencies. In this embodiment, radiation energy includes the radiation energy to modify the photonic density of states, but also the first and/or second additional radiation energy.

In a preferred embodiment, the photonic composite structure has a substantially cubic lattice structure. A cubic lattice structure implies a periodic lattice structure. This is preferably because it increases the chance of the occurrence of desired features in the photonic density of states, viz. for example a band gap. Of all the possible lattice structures the cubic lattice structure is the most preferred.

Preferably, the photonic composite structure has a substantially face-centered cubic lattice structure. Of all the cubic lattice structures, the face-centered cubic lattice structure has the highest chance of providing the above-mentioned features in the photonic density of states. The diamond lattice structure is to be included in the face-centered cubic lattice structure. The diamond structure may be considered a combination of such lattice structures, the one being translated along a quarter of the body diagonal with respect to the other. In a preferred embodiment of the device according to the invention, the photonic composite structure comprises, within a body comprising a first dielectric material, a substantially periodic structure of spaces comprising a second dielectric material. A particularly advantageous embodiment of this structure is the so-called inverse opal structure. Crystals with such a structure are prepared by first assembling a "template" made from suspensions of colloidal particles, e.g. silica particles, that order in face crystal structures. Next, the colloidal crystal is dried to form an artificial opal. A solid with a high refractive index is infiltrated in the void in the opal template, e.g. through a chemical reaction. Finally, the inverse opal is obtained by removing the template material by e.g. acid etching. This yields an ordered structure of approximately spherical voids filled with air that are connected in a high refractive index backbone. Usually there are small extra voids in-between the spherical void due to incomplete infiltration. Theory has it that both the windows between the spherical voids and the extra voids are favourable for the formation of photonic band gaps.

An alternative kind of photonic band gap crystals is made by etching a set of channels with a diamond symmetry in a slab of solid semiconducting material by methods known in the art. The empty channels, or voids in the inverse opals are filled with air to maximise the refractive index contrast with the solid material. Alternatively, the voids can be filled with liquids or low melting point solids to be able to tune the refractive index contrast. Further details will be discussed in connection with the description of the figures below.

In a preferred device according to the invention, at least one of the materials has been doped with impurities. Impurities may be present in a solid or liquid first material, in a solid, liquid, gaseous or "vacuum" second material, at an interface between these materials, or at combinations thereof. These impurities may serve as light sources inside the crystal. They may absorb or confine one or more photons. Practical impurities include excited quantum dots, quantum wells, atoms and ions including rare-earth ions, molecules including dye-molecules. Furthermore use may be made of electron-hole or excitonic recombination in the backbone material with a direct electronic band gap e.g. (GaAs), or in backbone material with an indirect band gap at sufficiently high temperatures to allow recombination to occur under the aid of e.g. phonons. It is to be noted that the presence of impurities is not necessary, since particles of the composite structure itself may also be excited through any means, e.g. photons or phonons, whereby these excited particles itself may serve as impurities.

In an advanced embodiment of the device, intentional defects are made in the photonic crystal, where the crystal symmetry significantly deviates locally from the substantially periodic structure. Point defects such as single vacancies may act as cavities with a high quality factor for frequencies in the band gap. Line defects may act as waveguides for frequencies in the band gap. A defect can have a strong effect on the local density of states. The invention allows for a device with a switchable coupling between a cavity and circuits outside the device, or a switchable coupling between a waveguide and circuits outside the device, or between a cavity and a waveguide inside the device, or between different cavities inside the device, or between different waveguides inside the device.

These and other advantages of the method and device according to the invention will now be further elucidated in connection with the description of the figures and examples.

The method and device according to the invention will now be further elucidated with reference to the drawing, in which: Fig. 1 diagrammatically shows an embodiment of a device according to the invention;

Fig. 2 diagrammatically shows the effect of supplying radiation on the real and the imaginary refractive index of crystalline Si; Fig.'s 3a,b show diagrams showing changes in the photonic band structure of a photonic crystal for three different indices of refraction; and Fig. 4a-d diagrammatically show the possible effects on the density of states for three kinds of frequencies. In Fig. 1, a photonic crystal 1 is shown. The inset shows that the crystal consists of a solid semiconductor backbone 2 surrounding air spheres 3, having impurities 4.

Two counterpropagating focussed laserbeams 5 are incident upon the crystal 1. Furthermore, a probe laserbeam 6 excites the impurities 4, which thereupon emit radiation 7, which is detected by detector 8.

Here, the photonic crystal 1 is an inverse opal. It consists of a solid backbone structure 2 comprising e.g. GaAs or silicon. Any other semiconductor or insulator could also be used, as well as liquid, such as e.g. an oily substance.

For a photonic crystal to show a photonic band gap, a few requirements should be fulfilled:

- 1) The ratio m of the real parts of the refractive index of the constituent materials should exceed a certain value, depending on the crystal structure. E.g., m should exceed 2.8 for a face-centered cubic lattice with close packed spheres, m should exceed 1.9 for a diamond lattice, and so on. Of course, if m does not exceed the appropriate value, there will be no band gap, but only frequency ranges with modified photonic density of states.
- 2) The optical absorption should be as small as possible.
- 3) The materials of the photonic crystal should be topologically interconnected.
- 4) The material with the highest refractive index (or dielectric constant, in practice) should be the minority.

An effective kind of photonic crystal, though not the only kind, is an inverse opal as described in the introductory part.

Suitable candidates for the high refractive index material are semiconductors to be used at frequencies below their electronic band gap energy, to avoid optical absorption to a large degree. Examples are III-V materials such as GaAs (refractive index $n = 3.4$, electronic band gap $= 1.4$ eV), GaP ($n = 3.3$, electronic band gap $= 2.25$ eV), and group IV materials such as Si ($n = 3.5$, electronic band gap $= 1.1$ eV) and Ge ($n = 4.0$, electronic band gap $= 0.7$ eV). Wide band gap semiconductors or insulators, such as TiO₂ ($n = 2.7$, electronic band gap $= 2.9$ eV) are favorable for uses in the visible energy ranges, but have limited refractive index. Based on the above data for refractive index, and electronic band gap energy, and on the constraints on the frequencies of the radiation to be used, it is possible to determine a suitable frequency, and thus wavelength, for probing radiation, i.e. radiation which is to convey information into, out of or through a photonic crystal. For Si a suitable wavelength is e.g. around 1940 nm, and for GaAs a suitable wavelength is 1550 nm,

which corresponds to a widely used telecom frequency.

In Fig. 1, 3 represents hollow spheres filled with air, although other gases, or even vacuum or liquids could do as well, provided their index of refraction is much lower than that of the backbone material 2.

The hollow spheres 3 comprise a number of impurities 4. These could be e.g. dye molecules, or quantum dots, or rare earth ions et cetera. The impurities could also be present in the backbone material 2, or on the interface of materials 2 and 3, or in the form of a vapor in material 3, or combinations thereof.

Impurities such as point defects inside a photonic crystal may be highly useful. In this way, cavities may be realized, that are well shielded from the perturbing vacuum, and thus have high quality factors or Q's. Examples of point defects are lattice vacancies, or extra added material at a lattice site. Similarly, a line defect may be placed in a lattice. This allows electromagnetic modes to propagate along such a line, but not through the bulk. Thus, the line defect acts as a kind of wave guide.

Two laserbeams 5 are incident upon the crystal 1. The laser frequency is selected according to the criteria for desired penetration depth, etc. It also depends on the materials of the crystal, which are to be excited. For silicon a wavelength of e.g. around 700 nm may be useful. The beams may be focussed, in order to obtain higher power densities. The beams may be cw or pulsed, depending on the desired power density. It is also possible to use only one laserbeam, or even more than two. A larger number of laserbeams ensures a better homogeneity of the excitation of the crystal 1.

Probe laserbeam 6 is used to excite the impurities 4. It is to be understood that the impurities may also be part of any of the constituent materials of the crystal 1 itself, or a vacancy or interstitial material or particle. By selecting a suitable frequency for the probe beam, particles of e.g. the backbone material may absorb this radiation, and become excited particles. Many times however, use will be made of specific impurities. After excitation by means of this probe beam 6, the excited particles will eventually reemit radiation 7. It will almost always be emitted in all directions. Part of this radiation 7 will be detected by detector 8. As described earlier, it is possible that the reemitted radiation is highly directional. In this case, the orientation of the detector becomes very important.

In the method according to the invention, the order in which the laserbeams 5 and the probe beam 6 are incident upon the crystal 1 depend on the desired effect. E.g. first probe beam 6 is supplied in order to excite particles with an emission frequency inside the original ground state band gap, hence emission of photons by the excited particles is prevented. Then, by supplying laser radiation 5 the ground state band gap may be removed and the excited particles are allowed to emit photons. When the band gap reopens again, due to relaxation of the induced free carrier plasma, the excited particles are again forbidden from emitting.

In an alternative method, probe photons with a frequency outside the ground state photonic band gap are supplied inside the photonic crystal 1 either externally from probe beam 6 or from emission of excited particles 4. By supplying laser radiation 5, the photonic band gap is shifted to include the frequency range of the probe photons. Said probe photons are then trapped inside crystal 1, likely near cavities consisting of defects in the crystal or near particles 4. When the band gap returns to the ground state, due to relaxation of the induced free carrier plasma or by supplying a modifier pulse by beam 5, the trapped photons may be released or re-emitted and detected.

The device shown may also be used to control the transmission of the probe beam 6, as follows.

First, when no laser radiation 5 is supplied, the photonic crystal has a photonic band structure, such that the crystal transmits the probe beam 6. When laserbeam 5 supplies adequate laser radiation to the crystal 1, the photonic band gap frequency range is shifted, such that the photon frequency of probe beam 6 is within this band gap. Now the crystal 1 no longer transmits probe beam 6, which phenomenon may be detected by the detector 8.

This set-up is not sensitive to the orientation of probe beam 6 and the crystal 1. Another possibility would be to control many different probe beams 6 with a single crystal 1. Thereto, a number of probe beams 6 could be directed at the crystal 1, each upon a different location of the crystal. Now for every beam 6 to be stopped, the region of the crystal corresponding with the location at which said beam 6 is incident, is to be supplied with laser radiation 5. This may be done simultaneously with some kind of mask, or e.g. by means of a control means which consecutively points a laser beam 5 at the different locations, in a time pattern short enough to prevent free carrier relaxation from shifting the photonic band gap back again. Fig. 2 shows the real (n') and imaginary (n'') refractive indices of crystalline silicon before (solid line) and after (dashed line) a free carrier plasma is excited, up to a density of

$1.9 \times 10^{19} \text{ /cm}^3$. This plasma is excited through laser pulses with pulse data 100 fs duration and 22 DJ energy, at a wavelength of 700 nm. A volume of $(100 \text{ Dm})^3$ of the silicon is assumed to be excited. This excitation shows an effect on n' over a large wavelength region. Since however n'' , which gives an indication for the absorption of the radiation, is also affected for wavelengths above some 1000 nm, an optimum wavelength for the desired effect should be selected to yield an as large as possible change in n' with an as small as possible increase in n'' . Here, a wavelength of 1940 nm is a good candidate, where the change of n' is about 8%, while n'' is still only about 0.0027. With similar pumping conditions, desired

effects can be optimized for wavelengths relevant to telecommunications, that is, near 1300 nm or 1550 nm.

Fig. 3a shows the photonic density of states per unit volume (DOS) vs. frequency D divided by speed of light c for a face-centered cubic inverse opal lattice with refractive index contrast $n^1 = 3.45$, e.g. silicon or GaAs, in combination with air in the hollow spheres. The photonic band gap occurs near a $\omega/c = 0.8$, a strongly decreased density of states occurs at the pseudo-gap near $\omega/c = 0.52$. Strongly increased density of states appear near $\omega/c = 0.56$ and 0.73 . Fig. 3b shows, in an enlarged view of a part of Fig. 3a as marked with the solid underscore, the DOS for the unexcited ground state with refractive index contrast $n^1 = 3.45$ (triangles), a first excited state with refractive index contrast $n^1 = 3.31$ (circles) and a second excited state with refractive index contrast $n^1 = 3.16$ (squares).

In the ground state, the refractive index $n^1 = 3.45$, and the band gap is between about 0.783 and 0.81. After supply of a first amount of laser radiation, n^1 has changed to 3.31, and the band gap has shifted to between about 0.81 and 0.833. After supply of another amount of laser radiation, n^1 has become 3.16 and the band gap is between about 0.846 and 0.861. Note also that the band gap is narrowed in this shift.

Furthermore, three vertical dashed lines indicate three frequencies of interest, I = 0.798, II = 0.833 and III = 0.857, for which the change in the DOS will be further elucidated in connection with Fig. 4.

In Fig. 4a is shown a diagram of the supplied power density versus time of the first laser pulse. This pulse corresponds to the pulse that shifts the DOS from the "triangles"-state to the "squares"-state in Fig. 3b.

The change in DOS as a function of time is represented in Fig. 4b. There, it can also be seen that the DOS for frequency I is essentially zero in the ground state ("triangles"), but about 5.2 after supply of the pulse ("squares"). Contrarily, for frequency II the DOS decreases from about 5.3 to essentially zero. In other words, possibly trapped radiation at a frequency I may be released with such a pulse, while radiation at a frequency II may be trapped with it. Fig. 4c represents the power density in time of two laser pulses being supplied to the crystal.

Fig. 4d represents the change in DOS for frequency III as a function of time.

The first of the two pulses being supplied corresponds to a pulse that changes the DOS from the ground state ("triangles") to a first excited state ("circles"). The second pulse corresponds to a pulse that changes the DOS from the first excited state to a second excited state ("squares"). For frequency III this means that the initial value for the DOS of about 0.8 changes to essentially zero after the first pulse. After the second pulse it has increased again to about 0.5. This means that by supplying two pulses the band gap may be opened and closed, within one picosecond.

It is to be noted that a long relaxation time of about 100 ps was assumed. Obviously, when no more radiation is supplied after the last pulse, the DOS will return to its original ground state value on time scales of the order of the relaxation time.

Examples of applications

1. A light source with fast on-switching. A photonic crystal has particles in an excited state, with frequencies in a photonic band gap. These particles may e.g. have been excited when the band gap was shifted or closed. Then through a laser pulse etc. the local density of states is increased very quickly from essentially zero to a relatively high value. The excited particles are suddenly allowed to emit light.
2. A light source with fast off-switching. A photonic crystal has excited particles, with frequencies outside a photonic band gap. Suddenly the density of states is modified by a laser pulse, such that the local density of states for the emission frequencies becomes essentially zero. The excited particles are no longer allowed to emit light.
3. A light source with fast off-on switching. A photonic crystal has excitable particles with excitation frequencies outside a band gap. A laser pulse very quickly modifies the density of states such that the band gap appears or is shifted to include the excitation frequencies. The particles cease to emit. A second laser pulse modifies the density of states further, such that the band gap disappears again or shifts to even higher frequencies. The particles start to emit again.
4. A light amplifier with fast on-, off-, or off-on switching. A large number of excited particles may be induced to emit light through supply of a weak light pulse, either from outside or generated inside the crystal. A laser pulse similar to the one in 1-3 determines the switching type and the switching time.
5. A laser with fast on-, off-, or off-on switching. This device is similar to 4, except that the number of excited particles is higher, and/or the excitation frequencies are chosen such that only few wave vectors are allowed for emission, whence laser action is obtainable.
6. Switchable multi frequency light source, -amplifier, -laser.

Several types of excitable particles are selected, each with different excitation frequencies. A series of laser pulses may switch the refractive index in steps. As a result, the frequency range of the photonic band gap also shifts in steps. Photons with the different stored frequencies, i.e. the different light sources, cavities etc., are switched on or off in increasing

frequency order. 7. Direction switch for light source, -amplifier, -laser. A photonic crystal with a band gap is selected in which the wave vector at the lowest gap frequency is different ("W-point") from that at the highest gap frequency ("X-point"). Assume a light source (or amplifier, or laser) emits at the lower edge of the band gap frequencies, and hence with a certain wave vector. By supplying a suitable pulse, the band gap shifts such that the same source now emits at an upper edge of the band gap frequencies, and hence with a controllably changed wave vector.

8. Photon memory device. Consider a photonic crystal with a defect cavity. Light with a frequency slightly above the band gap enters the crystal. A laser pulse switches the crystal, and the band gap is modified to comprise the incident photon frequency. Hence the photon is trapped near the cavity, and importantly, it is stored with full phase information etc. Note that it is not absorbed but reflects back and forth inside the cavity. A subsequent laser pulse may release the photon again.

This can be done for various colours with increasing frequencies, in order to obtain consecutive colours. Therefore one would need as many different and matching cavities as one wishes to store and re-emit light.

The coupling into and out of the cavity may be controlled as follows. This is to be compared to the normal, chance process. Consider a photonic crystal with a wave guide and a cavity, and hence with a photonic band gap. When the density of states is switched from low to high, the photons can go from the wave guide to the cavity or vice versa.

9. Controlled photon transfer. Consider a photonic crystal with N defect cavities, all with the same resonant frequency. Photons in one cavity are stored. The probability of spontaneous transfer to the neighbouring cavity decreases exponentially with distance, and may be neglected for sufficient inter-cavity distances. If the local density of states is changed in a region only between two cavities, photons are allowed to travel to this next cavity. Subsequent pulses which are directed at the desired intermediate locations between cavities may convey the photons through a crystal. Again it is noted that the photons do not lose any information, because they are not converted to a different form of energy.

Various other modifications of the disclosed embodiments of the invention will become apparent to persons skilled in the art upon reference to the description. It is therefore contemplated that the appended claims will cover such modifications or embodiments as fall within the true scope of the invention.

PATENTCITATIES

Geciteerd patent	Aanvraagdatum	Publicatiedatum	Aanvrager	Titel
US6058127 *	12 dec 1997	2 mei 2000	Massachusetts Institute Of Technology	Tunable microcavity and method of using nonlinear materials in a photonic crystal
US6181840 *	4 aug 1999	30 jan 2001	National Science Council	Reflectivity-tunable fiber optic reflector

* Geciteerd door patentambtenaar

NIET-PATENTCITATIES

Referentie	
1	* BLANCO A ET AL: "LARGE-SCALE SYNTHESIS OF A SILICON PHOTONIC CRYSTAL WITH A COMPLETE THREE-DIMENSIONAL BAND GAP NEAR 1.5 MICROMETRES" NATURE, MACMILLAN JOURNALS LTD. LONDON, GB, vol. 405, no. 6785, 25 May 2000 (2000-05-25), pages 437-440, XP001009789 ISSN: 0028-0836
2	* NAKAMURA H ET AL: "Large Enhancement of Optical Nonlinearity Using Quantum Dots Embedded in a Photonic Crystal Structure for All-Optical Switch Applications" PROCEEDINGS OF THE IEEE LASER AND ELECTRO-OPTICS SOCIETY 2000 ANNUAL MEETING (LEOS 2000), PISCATAWAY, NJ, USA, vol. 2, 13 - 16 November 2000, pages 488-489, XP001069029
3	* SCALORA M ET AL: "OPTICAL LIMITING AND SWITCHING OF ULTRASHORT PULSES IN NONLINEAR PHOTONIC BAND GAP MATERIALS" PHYSICAL REVIEW LETTERS, NEW YORK, NY, US, vol. 73, no. 10, 5 September 1994 (1994-09-05), pages 1368-1371, XP000949013 ISSN: 0031-9007
4	* YOSHINO K ET AL: "TEMPERATURE TUNING OF THE STOP BAND IN TRANSMISSION SPECTRA OF LIQUID-CRYSTAL INFILTRATED SYNTHETIC OPAL AS TUNABLE PHOTONIC CRYSTAL" APPLIED PHYSICS LETTERS, AMERICAN INSTITUTE OF PHYSICS, NEW YORK, US, vol. 75, no. 7, 16 August 1999 (1999-08-16), pages 932-934, XP000875542 ISSN: 0003-6951

* Geciteerd door patentambtenaar

VERWIJZINGEN NAAR DIT PATENT

Citerend patent	Aanvraagdatum	Publicatiedatum	Aanvrager	Titel
CN100444016C	24 mei 2004	17 dec 2008	中国科学院光电技术研究所	Photon crystal frequency conversion apparatus

CLASSIFICATIES

Internationale classificatie	G02B6/35 , G02F1/01
Coöperatieve classificatie	B82Y10/00 , G02F2202/32 , G02F1/0126 , G02F2202/13 , B82Y20/00
Europese classificatie	B82Y10/00 , B82Y20/00 , G02F1/01L

JURIDISCHE GEBEURTENISSEN

Datum	Code	Gebeurtenis	Beschrijving
-------	------	-------------	--------------

Datum	Code	Gebeurtenis	Beschrijving
27 maart 2003	AK	Designated states	Kind code of ref document: A1 Designated state(s): AE AG AL AM AT AU AZ BA BB BG BY BZ CA CH CN CO CR CU CZ DE DM DZ EC EE ES FI GB GD GE GH HR HU ID IL IN IS JP KE KG KP KR LC LK LR LS LT LU LV MA MD MG MN MW MX MZ NO NZ PH PL PT RO SD SE SG SI SK SL TJ TM TR TT TZ UG US UZ VN YU ZA
27 maart 2003	AL	Designated countries for regional patents	Kind code of ref document: A1 Designated state(s): GH GM KE LS MW MZ SD SL SZ UG ZW AM AZ BY KG KZ MD TJ TM AT BE CH CY DE DK ES FR GB GR IE IT LU MC NL PT SE TR BF BJ CF CG CI CM GA GN GQ GW MR NE SN TD TG
21 mei 2003	121	Ep: the epo has been informed by wipo that ep was designated in this application	
24 juli 2003	DFPE	Request for preliminary examination filed prior to expiration of 19th month from priority date (pct application filed before 20040101)	
10 nov 2004	122	Ep: pct app. not ent. europ. phase	
14 sept 2005	NENP	Non-entry into the national phase in:	Ref country code: JP

[Google Startpagina](#) - [Sitemap](#) - [USPTO-bulkdownloads](#) - [Privacybeleid](#) - [Servicevoorwaarden](#) - [Over Google Patenten](#) - [Feedback verzenden](#)

Gegevens geleverd door IFI CLAIMS Patent Services