

POLARIZATION ROTATOR

TECHNOLOGICAL FIELD

The present invention is in the field of polarization filters and more particularly relates to polarization rotation modules for use in arrays of electro-magnetic radiation receiving or transmitting elements.

5 BACKGROUND

Antenna arrays, and in general, arrays of modules for receiving and/or transmitting electro-magnetic radiation (hereinafter transceiver modules), are widely used for various applications. Such arrays may provide high reception/or transmission gains as well as the ability to control the directions of the transmission or reception
10 beams. The transceiver modules of an antenna array are, in many cases, arranged in a lattice defining tiling of reception and transmission modules that are typically similar to one another.

In some cases, polarization filters, such as a polarizer or polarization rotator, are arranged in front of the antenna array. Typically, the polarization filter is configured to
15 extend laterally over several or all of the transceiver modules so as to cover the fields of view of several of them.

Such a polarization filter may be configured for example utilizing several wire-grid layers each including an arrangement of parallel conductive lines (e.g. wires and/or printed conductive lines). The conductive lines are arranged parallel to one another
20 along a direction defining polarization extinction axis of the corresponding layer of the polarization filter. To this end, radiation components which are polarized parallel to the extinction axis of the layer, are reflected back or suppressed when interacting with the layer, and are therefore substantially prevented from being transmitted through the layer.

Examples of such wire-grid polarization filters are described for example in U.S. patent No. 6,788,461 and U.S. patent application publication No. 2006/0119937. Acknowledgement of these references herein is not to be inferred as meaning that these are in any way relevant to the patentability of the presently disclosed subject matter.

5 **GENERAL DESCRIPTION**

A highly desirable trait when designing an array of receiving and/or transmitting modules (transceiver modules such as antenna elements), is that the transceiver elements operate under similar intrinsic system conditions, and function in a similar way. For example, in some cases it may be desired that all the elements function in the
10 same way, or that the elements are grouped into one or more groups of elements operating under similar intrinsic conditions.

However, in some cases even when the similar or identical transceiver elements are used/deployed in an antenna array or other array of transceiver elements, there may still be some intrinsic conditions, which may have different effects on certain elements,
15 thus yielding somewhat different functional operations of the transceivers in the array. Such differences in intrinsic conditions may inter-alia result from a difference in the configuration/structure of a filter positioned in the "fields of view" of each of the transceiver elements.

The present invention provides a polarization filter for placement in front of an
20 array of transceiver elements/antennas. The polarization filter is configured in accordance with the arrangement of the elements/antennas in the array so as to have a substantially similar effect on all of the elements, or to have a substantially similar effect on a certain group(s) of elements in the array. To this end, the polarization filter configuration of the present invention reduces or eliminates any difference between the
25 intrinsic conditions to which different elements of the array are exposed. Particularly, the present invention provides a polarization filter system, and a method for applying polarization filtration to radiation propagating to, or from, an array of transceiver elements, while having a substantially similar effect on all of the transceiver elements, thereby reducing any differentiation between the intrinsic conditions to which the
30 different transceiver elements are exposed.

In this connection it should be noted that the term transceiver elements/modules is used herein to designate modules/elements that are capable of transmitting and/or

receiving electro-magnetic (EM) radiation. In particular, in the following, antenna elements/modules are considered, arranged to form an antenna array. To this end, for clarity, the terms *antenna elements* and/or *antenna modules* are used interchangeably to designate transceiver elements in general, and the phrase *antenna array* is used to designate an array of receiving and/or transmitting modules. However it should be understood that the terms antenna-module/element and antenna-array are used herein to designate in general any kind of modules capable of transmitting and/or receiving electro-magnetic radiation such as light source modules (e.g. lasers or light emitting diodes (LEDs)), optical detectors or emitters and others.

It should also be noted here that the term *internal/intrinsic conditions* is used herein to designate conditions that affect operation of the transceiver modules (of the antenna elements) and which are related to configuration of the system in which the antenna elements reside. This is as opposed to extrinsic conditions relating to the nature of the radiation propagating to/from the antenna elements and/or to the surroundings, external to the system, through which the radiation propagates.

A conventional configuration of a transmitting and/or receiving array (antenna array) including an array **TR** of antenna elements $E_{i,j}$ and a polarization filter **PR** is illustrated in **Fig. 1**. The conventional polarization filters **PR** used with such arrays are, in many cases, a source variable intrinsic conditions, which have different effect on different antenna elements $E_{i,j}$ of the array **TR**. For example, a polarization filter configured for rotating the polarization of the radiation passing therethrough by a certain polarization rotation angle α (e.g. 45°) may include a stack of wire-grid polarizers (here four polarizers **L1** to **L4**) arranged with different relative orientations so as to apply polarization rotation to radiation passing through the stack. Typically, the polarizers are implemented by patterned elements, such as conductive wire grid structures, with a certain spatial periodicity of the pattern. Accordingly, as the different polarizers are stacked with different relative orientations with respect to one another, the entire polarization filter **PR** of the conventional technique may have no spatial periodicity, (or it may be periodic only at very large length scales (e.g. in the order of, or larger than the entire antenna array)). For example, orientation angles α_1 to α_K of the polarizers in such filters are in many cases selected so as to equally divide the polarization rotation angle α (e.g. $\alpha_k = (k-1)*\alpha/(K-1)$ where $\alpha_1=0^\circ$, K is the number of polarizers and k is the polarize index in the stack). Thus, in a four layer ($K=4$)

polarization filter for rotating the polarization by a total polarization rotation angle $\alpha=45^\circ$, the orientation angles of the polarizer layers might be conventionally selected as follows: 0° , 15° , 30° , and 45° .

However, a major deficiency in conventional techniques for designing such polarization rotation filters/modules is that conventional polarization filters **PR**, including more than two polarizers (i.e. for which $K>2$), may have no spatial periodicity of relatively long length scale (larger than the periodicity of the antenna elements' array) which is meant to be placed behind of the polarization rotation filter **PR**. This may result in each of the transceiver/antenna elements $E_{i,j}$ "seeing" a different configuration/pattern of the polarization filter **PR** in its field of view. As a result, the polarization rotation filter **PR** may have a different effect on different antenna elements $E_{i,j}$, which either deteriorates the performance of such system as a whole, or is required to be taken into account during the design stage of such a system. In the latter case, specific computations and/or simulations are typically required for each of the antenna elements (e.g. during the system design/calibration stage(s)) to estimate their operation, while including the different intrinsic effects that such a polarization rotation filter has on the different elements. However, this may be highly computationally intensive, and may result in less than optimal operation of the antenna system, and, additionally, might require extensive time and computational resources at the stages of system design and/or at later stages (e.g. at a system calibration stage).

The present invention provides for solving such problems which exist in conventional techniques. According to some aspects of the present invention, the polarizer is configured in accordance with the arrangement of the array of transmitting/receiving elements that is to be located behind it, such that one or more pluralities/groups of transmitting/receiving elements are exposed to substantially similar patterns of the polarization rotator in their fields of view. This simplifies the design of the system and/or its calibration, since each group of transmitting/receiving elements, together with their respective part of the polarizer, being in their field of view, are similar to one another in configuration and in operation.

According to a broad aspect of the present invention, provided is a polarization rotator (polarization rotation filter) including a plurality of polarizer layers stacked along a general direction of radiation propagation therethrough. Each of the polarizer layers implements a respective wired grid pattern which defines a respective extinction

axis, such that extinct components of the radiation are polarized along that respective extinction axis when radiation interacts with the respective polarizer layer. Also, each pair of consecutive polarizer layers of the polarization rotator are arranged such that their respective extinction axes have different orientations, thereby affecting polarization rotation of the radiation interacting with the polarization rotator. According to some aspects of the present invention the wire-grid patterns of the polarizer layers are configured as continuous patterns defining relative orientations of the extinction axes such as to define, in the polarization rotator, a tiling of a plurality of substantially identical polarization rotation unit cells, which are arranged with predetermined respective spatial periods A and B along two lateral axes spanning the tiling.

According to another broad aspect of the present invention there is provided a radiation module (e.g. antenna module) including an array of elements (i.e. receiving, transmitting, or transceiving elements; e.g. antenna elements), and a polarization rotator which is configured according to the present invention and defines a tiling of a plurality of substantially identical polarization rotation unit cells. The elements are arranged in a plane substantially parallel to the tiling of the plurality of the polarization rotation unit cells. More specifically, the elements are arranged with respective spatial periodicities A' and B' along each of the two lateral axes spanning the tiling, where the respective spatial periodicities A' and B' are, respectively, integer multiples of the predetermined spatial periods A and B of the polarization rotation unit cells. Accordingly, the antenna elements are exposed to substantially similar wire-grid patterns of the polarization rotator's layers in their respective fields of view.

According to some embodiments of the present invention the lateral extent of the polarization rotator is configured to be greater than a lateral extent of the arrangement of elements/antennas along the two lateral axes spanning the tiling such that the field of view of each of the elements is entirely covered by the polarization rotator. Also, in some embodiments, each of the elements/antenna-elements is associated with one or more of the polarization rotator unit cells covering its field of view.

According to some embodiments of the present invention the polarization rotator includes a number of N polarization rotation layers. The layers are arranged in a stack and configured for rotating the polarization of the radiation by a predetermined angle α . In some embodiments the number of polarization rotation layers N is selected in

accordance with a desired width $\Delta\lambda$ of the operational wavelength band of the polarization rotator such that for wider bands a greater number of layers N is used. Also, in some embodiments a ratio between the predetermined spatial periods, A and B , of the tiling of the substantially identical polarization rotation unit cells along said two lateral axes respectively is given by $A/B = \tan(\alpha)/(N-1)$. The polarizer layers in the stack may be configured according to the invention such that the extinction axes thereof are oriented with orientation angles $\alpha_k = \tan^{-1}((k-1)A/B)$ where k indicates the location of the polarizer layer in the stack.

According to some embodiments of the present invention the polarizer layers of the polarization rotator include continuous wire-grid patterns which are formed with corresponding respective pitches d_k selected such that the continuous wire-grid patterns are periodic along a certain lateral axis with spatial periodicity $N*d$, where N is an integer number and d is a predetermined value associated with a nominal pitch distance. To this end the predetermined respective spatial period A of the unit cells along the certain lateral axis may be given by $A = N*d$. Also the respective pitches d_k of the continuous wire-grid patterns of polarizer layers may be selected to satisfy $d_k = d*N_k*\cos(\alpha_k)$, where N_k is an integer or a rational number associated with each polarizer layer k respectively, and α_k is the orientation of the respective polarizer layer k . In some specific cases the respective pitches d_k of the continuous wire-grid patterns of polarizer layers satisfy $d_k = d*\cos(\alpha_k)$.

According to some embodiments of the present invention the continuous wire-grid pattern of each polarizer layer is formed as an arrangement of a plurality of continuous conductive line regions spaced apart from one another and oriented along the extinction axis of the polarizer layer. For example the continuous conductive line regions of the wire-grid pattern may be spaced from one another at a distance of less than a nominal wavelength λ of the radiation which is to be polarized. In some implementations at least some of said polarizer layers include a dielectric substrate with the plurality of continuous conductive line regions printed thereon. Also, in such implementations, one or more spacer layers may be arranged in between at least two of the polarizer layers. For example the dielectric substrate may include at least one of a ceramic and glass-reinforced epoxy laminate material, and the spacer layer may include structural foam. In some implementations the conductive line regions of at least one polarizer layer may be formed utilizing conductive wires arranged in the layer.

According to another broad aspect of the present invention there is provided an antenna including an array of antenna elements and a polarization rotator. The antenna elements of the array are arranged with spatial periodicities, A' and B', with respect to two lateral axes of the antenna. The polarization rotator includes a stack of a plurality of
5 K polarizer layers which are stacked along a general direction of radiation propagation to or from the antenna elements. The plurality of K polarizer layers respectively implement continuous wired grid patterns oriented so as to rotate the polarization of the radiation. According to some aspects of the present invention each polarizer layer, indexed k in the stack, is oriented with orientation angle $\alpha_k = \tan^{-1}((k-1)(n*A')/(m*B'))$,
10 where k is an index of a corresponding polarizer layer k in the stack of K layers and n and m are predetermined integers.

According to some embodiments of the present invention the antenna is configured/implemented utilizing as an integrated structure which includes at a stack printed circuit boards. The stack of printed circuit boards includes least one printed
15 circuit layer with the antenna array printed thereon, and one or more printed circuit board with one or more of the polarizer layers printed thereon. In some embodiments the antenna elements of the array are arranged with spatial periodicity A' along a certain axis, and the polarization rotator is configured to rotate the polarization of the radiation by an angle α . Accordingly the spatial periodicity B' with respect to the other lateral
20 axes of the antenna is selected such that $B' = (n*A')/(m*\tan(\alpha))$.

To this end, the array of antenna elements may be implemented as a one dimensional array. Alternatively, the array of antenna elements may be implemented as a two dimensional array of antenna elements.

In some embodiments of the present invention the antenna elements may be
25 arranged in a rectangular lattice with spatial periodicities A' and B' along the two respective axes spanning the lattice. This feature may be used to provide that the antenna elements are exposed to substantially similar wire-grid patterns of the polarization rotator's layers in their respective fields of view.

In some embodiments of the present invention the antenna elements may be
30 arranged in a Triangular or an Hexagonal lattice with spatial periodicities A' and B' along two axes spanning the lattice respectively. The antenna elements may thereby be associated with two or more groups of antenna elements, wherein the antenna elements

of each group are exposed to substantially similar wire-grid patterns of the polarization rotator's layers in their fields of view.

According to some embodiments of the present invention the continuous wire-grid patterns of the polarizer layers of the antenna are formed with corresponding
5 respective pitches d_k satisfying $d_k = d * N_k * \cos(\alpha_k)$, where d is a predetermined value, N_k is an integer or a rational number associated with each polarizer layer k respectively, and α_k is the orientation of the respective polarizer layer k . This provides that the continuous wire-grid patterns of the polarization layers have a common spatial periodicity along a certain lateral axis of the antenna.

10 According to yet another broad aspect of the present invention there is provided a method for use in applying polarization rotation to radiation. The method includes providing data indicative of a total polarization rotation angle α to be applied to radiation interacting with a polarization filter module comprising a stack including a number K of polarizer layers, and setting an orientation angle α_k of each polarizer layer
15 k of said K polarizer layers as $\alpha_k = \tan^{-1}(\tan(\alpha)(k-1)/(K-1))$. Here k is the index of said polarizer layer in the stack of K polarizer layers. According to some embodiments of the present invention, the method further includes providing a desired ratio A/B between spatial periodicities A and B to be obtained in the polarization filter module with respect to two lateral axes thereof respectively. Then, determining the number K of polarizer
20 layers base on that ratio as follows: $K = 1 + (B/A) * \tan(\alpha)$.

According to some embodiments of the present invention one or more of the polarizer layers are implemented as/utilizing respective wire-grid patterns. Accordingly, the method of the present invention may further include selecting the pitches d_k of the respective wire-grid pattern of the one or more polarizer layers based on the respective
25 index k and the orientation angle α_k of each of these one or more polarization layers as follows: $d_k = d * N_k * \cos(\alpha_k)$. Here d is a predetermined value, N_k is an integer or a rational number associated with each of the polarizer layers. In some cases N_k may be selected to be 1 for some or all of these one or more layers and thus $d_k = d * \cos(\alpha_k)$.

Various features and advantages of the present invention are described in more
30 detail in the description section below. It should be understood, and will be apparent to a person of ordinary skill in the art, that various modifications and implementations which are not specifically described herein, may be applied to the technique of the present invention without departing from the scope of the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

In order to better understand the subject matter that is disclosed herein and to exemplify how it may be carried out in practice, embodiments will now be described, by way of non-limiting example only, with reference to the accompanying drawings, in
5 which:

Fig. 1 is a schematic illustration of a conventional configuration of an antenna array module including a polarization rotator;

Figs. 2A to 2E schematically illustrate a polarization rotator module **100** configured according to an embodiment of the present invention;

10 **Fig. 3** is a flow chart **200** illustrating a method for designing a polarization filter module **100** according to an embodiment of present invention; and

Figs. 4A and 4B are schematic illustrations of two radiation/antenna modules **300** configured according to two embodiments of the present invention.

DETAILED DESCRIPTION OF EMBODIMENTS

15 Reference is now made to **Fig. 2A** schematically illustrating the configuration of a polarization rotator module **100** (e.g. filter) according to an embodiment of the present invention. As illustrated the polarization rotator **100** includes a plurality of **K** polarizer layers **PL₁** to **PL_K** stacked one on top of the other (e.g. stacked along a general direction **Z** of radiation propagation through the polarization rotator module **100**). In the
20 following, a capital **K** is used to denote the total number of polarizer layers in the polarization rotator module **100**, and **k** indicates the order index of each layer in the stack ($1 \leq k \leq K$). Each layer **PL_k** of the polarizer layers **PL₁** to **PL_K** is configured as a polarization filter associated with a certain respective extinction axis **EX_k** and is adapted to filter (e.g. extinct / reflect back) radiation components which are polarized along the
25 extinction axis **EX_k** when interacting with /incident on the layer **PL_k**. The polarizer layers **PL_k** implement respective patterns **PT_k** defining the directions/orientations **a_k** of their respective extinction axes **EX_k**. Accordingly, the layers **PL₁** to **PL_K**, e.g. their respective patterns **PT_k** and the orientations **a_k** thereof, are configured to affect polarization rotation to radiation successively interacting therewith. To this end,
30 respective extinction axes **EX_k** of different polarizer layers **PL_k** are differently oriented, so as to rotate the polarization of radiation interacting with the polarization rotator module **100**.

According to some embodiments of the present invention, the patterns $\mathbf{PT}_k$ implemented by the respective polarizer layers $\mathbf{PL}_k$ are configured as continuous patterns. The patterns $\mathbf{PT}_k$ of the polarizer layers $\mathbf{PL}_k$ are arranged such that the extinction axes $\mathbf{EX}_1 - \mathbf{EX}_K$ of the layers are oriented with orientation angles α_1 to α_K ,
5 that are specifically selected such that a plurality of substantially identical polarization rotation unit cells $\mathbf{UC}_{n,m}$ are defined by the polarization rotator module **100**. More particularly, as illustrated in the **Fig. 2A**, the polarization rotator module **100** of this example can be sectioned into 25 polarization rotation unit cells $\mathbf{UC}_{1,1}$ to $\mathbf{UC}_{5,5}$ having similar configurations and arranged in a two dimensional tiling (e.g. defining a lattice of
10 unit cells $\mathbf{UC}_{n,m}$ of similar configurations and electrical/optical properties). In this connection, it should be understood that although in this and the following examples, a two dimensional arrangement/tiling of such polarization rotation unit cells is described, a person of ordinary skill in the art will readily appreciate that the same technique can also be used to configure the polarization rotation module **100** to define a one
15 dimensional tiling of similar unit cells.

As indicated above and will be further exemplified in more detail below, the configuration of the polarization rotator module **100** of the invention, defining the plurality of similar unit cells, allows to place the polarization rotator module **100** in front of an array (1D or 2D array) of radiation transmitting and/or receiving elements
20 (e.g. antenna elements) such that the transceiving elements are exposed to substantially similar patterns of the polarization rotator's layers in their respective fields of view. Accordingly, the polarization rotator module has the same effect on all the transceiving elements. This may obviate a need to separately design and/or calibrate the reception/transmission operation of each of the transceiving elements in accordance
25 with the particular configuration (e.g. layer patterns) of the section of the polarization rotation module which is located in front of it in its field of view.

As indicated above, according to certain embodiments of the present invention, the angles α_1 to α_K of the respective patterns $\mathbf{PT}_k$ of the polarizer layers $\mathbf{PL}_k$ (e.g. the orientations of their respective extinction axes $\mathbf{EX}_k$) are specifically selected in
30 accordance with the desired dimensions/special periodicities **A** and **B** of the desired unit cells $\mathbf{UC}_{n,m}$ to be defined in the polarization rotator **100**. Here **A** and **B** designate the dimensions/periodicities of the unit cells along the two lateral axes **X** and **Y** of the polarization rotator **100** respectively. As will be described in more detail below, the

dimensions/special periodicities **A** and **B** of the desired unit cells are generally associated with the spatial periodicities of the antenna elements array to be located behind the polarization rotator **100**. More particularly, according to some embodiments of the present invention the respective orientations α_k of the patterns **PT_k** and/or that of the extinction axes defined thereby **EX_k** are selected in accordance with the following formula:

Eq. (1) $\alpha_k = \tan^{-1}((k-1)A/B)$

where k indicates the index of the location of the polarizer layer **PL_k** in the stack of polarizer layers in the polarization rotator **100** and A and B are the spatial periodicities/dimensions of the polarization rotation unit cells **UC_{n,m}** along the lateral axes X and Y respectively. Note that $\alpha_1 = 0^\circ$, which is the orientation angle of the pattern **PT₁** (or of the extinction axis **EX₁** thereof) of the first layer **PL₁** is used here as a reference, relative to which the angles α_k of the patterns of all of the other polarization layers **PL_k** are measured.

It should also be noted that the terms *spatial periodicities* and *dimensions* (i.e. A and B) of the unit cells **UC_{n,m}** are used here interchangeably. The angles α_k are in fact determined based on the desired spatial periodicities A and B of the unit cells tiling along the lateral directions X and Y respectively. However, as the unit cells are considered to be tightly packed, A and B also designate the lateral dimensions thereof.

As illustrated in the figure, according to some embodiments of the invention, the patterns **PT_k** of the polarization layers **PL_k** may be implemented as wire grid patterns, each formed as an arrangement **CL_k** of a plurality of substantially parallel and continuous conductive line regions, which are spaced apart from one another and oriented along the respective extinction axis **EX_k** of its corresponding polarizer layer **PL_k**. Accordingly, radiation components polarized along the conductive lines **CL_k** induce electric current in the conductive lines and are thus substantially reflected/absorbed thereby when interacting with the polarizer layer **PL_k**, while other polarization components (e.g. polarized perpendicularly to the conductive lines) are substantially not absorbed/reflected but mostly substantially pass the polarizer layer **PL_k** un-affected.

In this connection, the d_k pitch distance of conductive lines **CL_k** of the respective wire grid patterns **PT_k** is typically selected to be smaller than the nominal wavelength λ_n of the wavelength band of the radiation that is to be affected (its polarization rotated) by the polarization rotator module **100**. In other words the

conductive lines $\mathbf{CL}_k$ of the wire grid patterns $\mathbf{PT}_k$ are typically spaced apart from one another with distances $\mathbf{d}_k$ substantially smaller than the nominal wavelength λ_n ($\mathbf{d}_k \ll \lambda_n$) in order to provide efficient extinction (e.g. reflection) of radiation components polarized along the conductive lines $\mathbf{CL}_k$.

5 According to some embodiments of the present invention, the number K of polarization rotation layers $\mathbf{PL}_k$ may be selected in accordance with the width $\Delta\lambda$ of the wavelength band of the radiation considered and total angle α by which the polarization of the radiation is to be rotated by the polarization rotator **100**. For example, for larger polarization rotation angles α and/or for broader band widths $\Delta\lambda$, a greater number K of
10 polarizer layers $\mathbf{PL}_k$ may generally be used. Thus, proper selection of the number K of polarizer layers provides that polarization of radiation with wavelengths λ being in the bandwidth $\lambda_n - \Delta\lambda < \lambda < \lambda_n + \Delta\lambda$ can be effectively rotated by the polarization rotator **100**. The separation/spacing S between consecutive polarizer layers (i.e. along the axis Z perpendicular thereto) is typically selected in the order of $S \sim \lambda_n/4$. This provides for
15 efficient polarization rotation operation of the polarization rotator module **100** to radiation of wavelengths λ .

Referring together to **Figs. 2B to 2E**, illustrated are sections S_1 to S_4 which are corresponding sections of polarization layers $\mathbf{PL}_1$ to $\mathbf{PL}_4$ of a polarization rotator module **100** that is configured similarly to the polarization rotator module exemplified
20 in **Fig. 2A**. In this non limiting example, the polarization rotator module **100** includes a total of $K=4$ polarization layers $\mathbf{PL}_1$ to $\mathbf{PL}_4$. Sections S_1 to S_4 , which are respective parts of the polarization layers $\mathbf{PL}_1$ to $\mathbf{PL}_4$, encompass three polarization rotation unit cells $\mathbf{UC}_{1,1}$ $\mathbf{UC}_{1,2}$ $\mathbf{UC}_{1,3}$, having dimensions A and B along the two lateral axes X and Y respectively. The polarization rotator module **100** is configured to filter one of the
25 polarization components of radiation interacting therewith (e.g. filter the component that is parallel to the extinction axis of the first polarizer layer it interacts with (e.g. filter the polarization component parallel to $\mathbf{EX}_4$) and also to rotate the polarization of the second polarization component of that radiation (e.g. rotate the polarization component orthogonal to $\mathbf{EX}_4$) by a total polarization rotation to angle α (e.g. so it
30 becomes orthogonal to the extinction axis $\mathbf{EX}_1$ of the last polarizer layer with which the radiation interacts on the way to the antenna array).

The lateral dimensions A and B of the smallest possible unit cell $\mathbf{UC}$ can be determined based on the following equation:

Eq. (2) $A/B = \tan(\alpha)/(K-1)$

The unit cell UC represents the smallest repeatable "building block" sections/structures defined in the polarization rotation module 100. The polarization rotator 100 may be regarded as a tightly packed tiling of a plurality of similar such unit cells UC seamlessly "stitched" together.

In the present example of Figs. 2B to 2E, the total polarization rotation angle α was selected to be $\alpha = 45^\circ$ and the number K of polarizer layers is 4. Accordingly the ratio of the unit cell's lateral dimensions A and B, satisfy $A/B = \tan(\alpha)/(K-1) = 1/3$. Given a desired one of such lateral dimensions/periodicities of the unit cells (A or B), the other one of them can thus be determined. To this end the desired lateral dimension (A or B) may be determined based on a periodicity of the antenna/transceiver array which is to be located in front of the polarization rotator.

As can be seen in Figs. 2B to 2E, in each layer PL_k of the polarizer layers PL_1 to PL_4 of the polarization rotation module, unit cell sections can be stitched together to form a continuous wire-grid pattern in the layer, without any discontinuity of the pattern (e.g. of the conductive lines in the pattern) in the border line between adjacent unit cell sections. Accordingly, an array of antenna elements (or, more generally, array radiation receiving and/or transmitting modules) may be arranged in front of the polarization rotation module 100 with spatial periodicities $A' = n \cdot A$ and $B' = m \cdot B$ between the antenna elements in the array, to thereby provide that the antenna elements are exposed in their respective fields of view to the similar structures/patterns of the polarization rotation module's layers.

This is achieved according to the invention by properly selecting the orientation angles α_k of the wire-grid patterns PT_k of the respective layers PL_k (indexed k). More specifically, according to some embodiments of the present invention the orientation angles are selected in accordance with the desired lateral dimensions of the unit cells (the ratio between them) as in Eq. 1 above. Alternatively or additionally, as the ratio A/B may depend on the number of polarizer layers K and the total angle of polarization rotation α , the orientation angles α_k may be computed based on these parameters as follows:

Eq. (3) $\alpha_k = \tan^{-1}(\tan(\alpha)(k-1)/(K-1))$.

It should be noted that the total number of polarizer layers K may be selected based on Eq. (2) above in accordance with the desired ratio A/B of the lateral

periodicities/ lateral dimensions of the unit cells and the total polarization rotation angle α . In such a case, the orientation angles α_k may be selected in accordance with Eq. (1) above, based on the desired ratio A/B of the lateral periodicities/ lateral dimensions of the unit cells.

5 Alternatively or additionally, the number K of polarizer layers may be predetermined in advance. For example, K may be a given design parameter, which may be selected to approximate the ratio A/B while also to optimize operation of the polarization rotation in the desired bandwidth $\Delta\lambda$ considering that for wider desired bandwidth $\Delta\lambda$ a higher number K of polarizer layers should preferably be used.
10 Accordingly, in case K is a given parameter, the orientation angles α_k may be selected in accordance with Eq. (3) above, based on K and on the total polarization rotation angle α .

To this end, according to some embodiments of the present invention the spacing d_k between the conductive lines/wires (the pitches of the conductive lines d_k in
15 each of the patterns PT_k) are also specifically selected to provide that the wire grid patterns PT_k , in each of the layers k respectively, are formed as continuous wire-grid patterns across the entire polarization rotation module **100**. To this end, the unit cells of the polarization rotator **100** module are similar in their configuration (and layer pattern structures) and also no discontinuities are formed in the border between unit cells. In
20 some embodiments, this may be achieved by selecting the pitches d_k conductive lines at each layer polarizer layer PL_k respectively as follows:

Eq. (4) $d_k = d \cdot \cos(\alpha_k)$

Where d is a certain predetermined nominal pitch distance of the conductive line and α_k is the orientation angle of the wire-grid polarizer pattern in the respective layer indexed
25 k. Typically, d is selected to be smaller than the nominal wavelength λ of the radiation whose polarization is to be rotated. In this connection, it should also be noted that in the present example $d \equiv d_1$ actually defines the spatial period A of the unit cells ($d = A$).

More generally, it should be understood that the pitch distances d_k are selected such that the respective wire-grid patterns PT_k are all periodic along a certain lateral
30 axis (e.g. X) with spatial periodicity $N \cdot d$ (where N is a certain integer number). To this end, the predetermined spatial period A of the unit cells may be given by $A = N \cdot d$. Thus,

in the general case, this condition may be satisfied by selecting pitches d_k of conductive lines at each respective polarizer layer PL_k as follows:

Eq. (5) $d_k = d * N_k * \cos(\alpha_k)$

where d is the predetermined nominal pitch distance, N_k is an integer or a rational number associated with conductive line pitches in each polarizer layer k , and α_k is the orientation of the layer. Accordingly, the spatial period A of the unit cells is given by:

Eq. (6) $A = N * d$ where $N = \text{Max} \{N_k\}$

It should be understood that the widths of the W_k of conductive lines, in each layer k , are typically smaller than the spatial-periodicity/pitch d_k of the conductive lines so that the conductive lines are spaced apart from one another. This is in order to reduce the effects of the polarizer layer k on radiation components which are polarized perpendicular to the conductive lines of the layer, while reflecting the radiation components which are polarized parallel to the conductive lines of the layer. To this end, it should be understood that the widths of the W_k of conductive lines may be the same or different in different layers k .

Fig. 3 is a flow chart **200** of a method for designing a polarization filter module **100** (polarization rotator module) according to the present invention. Method **200** includes operations 210 to 290 described forthwith.

Both **210** and **220** show data indicative of a total polarization rotation angle α to be applied to radiation interacting with the polarization filter module **100**, and data indicative of the nominal wavelength λ of the radiation and possibly also of the bandwidth $\Delta\lambda$ of the radiation wavelength. In operation **230**, a desired number K of polarizer layers PL_k to be implemented in the polarization rotation module **100** is provided/determined. The number K may be provided as a predetermined design parameter and/or it may be selected/determined based on the desired bandwidth $\Delta\lambda$ and/or based on the desired dimensions/periodicities A and B of the unit cells.

In this connection in operations **240** and **250**, the desired lateral dimensions/periodicities A and B of the unit cells' tiling to be defined in the polarization rotation module **100** are determined. For example, in **240** one of these desired periodicities (e.g. the length A or the width B of the unit cells) may be provided, and the other one of these desired periodicities may be determined in **250** by utilizing the ratio A/B which may be calculated based on Eq. (2) and utilizing α and K which are provided

in operations **210** and **230** above. Operations **240** and **250** can be performed before or after operation **230**.

In **260**, the orientation angles α_k of the patterns of the polarizer layers PL_k are determined. For example, the orientation angle α_k of the extinction axis of each polarizer layer PL_k can be determined according to based on the layer's index k based on Eq. (1) or Eq. (3) above (e.g. utilizing either the desired unit cell dimension ratio A/B or the desired number of layers K as given parameters).

In optional operations **270** and **280** the pitches d_k of the conductive lines/wires in the wire grid patterns PT_k of the respective polarizer layers PL_k are determined. In **270** a nominal pitch is provided/selected, typically in accordance with the radiation wavelength; e.g. $d \ll \lambda$, and in **280** the pitch d_k of the wires/conductive lines in each layer is selected in accordance with the pattern α_k orientation in each layer k (e.g. according to Eq. 4 or 5 above).

In this regard it should be noted that not only the pitches d_k of different polarizer layers PL_k may have different values, but that accordingly, also the values of the widths W_k of conductive lines may be specifically selected/determined in **280** (e.g. based on the respective pitches d_k of the corresponding layers k) so as to optimize the operation of the polarization rotation module. To this, widths W_k of conductive lines may have the same or different values in different layers k .

In optional operation **290** the arrangement of the receiving and/or transmitting elements of an antenna array is determined in accordance with the dimensions A and B of the unit cells defined. More specifically the spatial periodicities A' and B' of the receiving and/or transmitting elements of the arrays may be selected according to Eq. (7) as integer multiples of the respective spatial periods A and B of the polarization rotation unit cells.

$$\text{Eq. (7)} \quad A'=m*A \text{ and } B'=n*B \quad \text{where } n \text{ and } m \text{ are integer numbers.}$$

To this end, considering Eq. (1) above, given a predetermined desired spatial periodicities A' and B' of the receiving and/or transmitting elements, the orientation angles α_k of the wire-grid patterns PT_k in the stack of the polarization rotation module may be selected as follows:

$$\text{Eq. (8)} \quad \alpha_k = \tan^{-1}((k-1)(n*A')/(m*B'))$$

This provides that fields of view (e.g. reception/transmission beams of the antennas) of the receiving and/or transmitting antenna elements are exposed to substantially similar wire-grid patterns of the polarization rotator's layers. In other words, the antenna elements are each associated with a certain number of one or more polarization rotator unit cells covering their fields of view (e.g. covering their reception/transmission beams) and located at the same relative positions with respect to the antenna elements associated therewith.

Reference is now made together to **Figs. 4A** and **4B** illustrating two examples of a radiation/antenna module **300**. As shown in these figures, the radiation module **300** includes a polarization rotation module **100** configured according to an embodiment of the present invention, and an arrangement/array **310** of radiating elements. For clarity, the radiating elements are herein after also referred to as *antenna elements* or just *elements*, although it should be understood that types of radiation elements may also be used and are also considered in the scope of the present invention. The radiating/antenna elements are arranged/tiled to form different types of a two-dimensional array. The antenna elements of the array **310** are arranged in a plane substantially parallel to the plane of the polarization rotator module **100** (namely parallel to the polarizer layers **PL_k** thereof). It should be noted, although not expressly depicted in the figure, that according to some embodiments of the present invention the polarization rotator module **100** is configured with a lateral extent greater than a lateral extent of the arrangement of elements along the two lateral axes X and Y such that the field of view (the reception/transmission beam) of each of the antenna elements (e.g. including those elements located at the margins of the array) is entirely covered by the polarization rotator module **100**.

Fig. 4A illustrates an antenna module **300** including an array **310** of antenna elements $E_{n,m}$ arranged in a rectangular lattice with spatial periodicities A' and B' along the two lateral axes X and Y, and a polarization rotator module **100** configured according to the present invention and accommodated in front of the array **310** of antenna elements $E_{n,m}$. The number of polarizer layers K of the polarization rotator module **100** and the orientations α_k of their respective extinction axes EX_k were selected according to the present invention, to define in the polarization rotator module **100**, a tiling of unit cells arranged with spatial periods $A = A'/m$ and $B = B'/n$, where n and m are integers. In the present illustration $m = 3$ and $n = 1$. A rectangular lattice **RL** with

periodicities A' and B' along the X and Y axes is illustrated in the figure and its projection onto each of the polarizer layers is also shown. It should be understood that the rectangular lattice **RL** is not an element of the antenna module **300** but is illustrated in the figure only to serve as a guide to the eye, to illustrate that cells in the lattice "see" similar wire-grid polarizer layer patterns.

Fig. 4B illustrates an antenna module **300** including an array **310** of antenna elements $E_{n,m}$ arranged in a hexagonal lattice with spatial periodicities A' and B' , and a polarization rotator module **100** similar to that of **Fig. 4A** accommodated in front of the array **310**. The hexagonal lattice **HL** is illustrated in the figure together with its projection onto each of the polarizer layers to serve as a guide to the eye. As can be seen in the hexagonal lattice **HL** there are defined two groups of cells respectively accommodating elements E^1 and E^2 , and the elements in each group of cells lattice "see" similar patterns of the wire-grid polarizer layers. Namely the antenna elements $E1$ are all exposed to a similar structure of the polarization rotation module **100** in their fields of view, and in the same way the antenna elements **E2** are also all exposed to a similar pattern structure of the polarization rotation module **100**. To this end, utilizing the hexagonal lattice provides that there are two groups of antenna elements wherein the elements of each group experience a similar optical/electrical effect from the polarization rotation module **100**.

In the examples of **Figs. 4A** and **4B** a rectangular array of antenna elements (**Fig. 4A**) and a hexagonal array of antenna elements (**Fig. 4B**) are respectively illustrated in conjunction with the polarization rotator module **100**. It will be readily appreciated by those versed in the art that the present invention may also be implemented with different types/geometries of arrays of receiving and/or transmitting elements. For example, the polarization rotator module **100** may be configured for use with one dimensional arrays or with two dimensional arrays of antenna elements. Also, according to various embodiments of the present invention, the polarization rotator module **100** may be used with other array geometries (other lattice types) such as triangular or rhombus arrays of antenna elements. Yet further, according to various embodiments of the present invention, the polarization rotator module **100** may be used with composite arrays of antenna elements formed as two or more superimposed arrays of elements, where the periodicities A' and B' of each of the superimposed arrays each satisfy Eq. (7) above. In this connection, the antenna elements of each of the

superimposed arrays may be laterally shifted, or with respect to the other of the superimposed arrays, by a non-integer number of unit cell periods A and B along the lateral X and Y axes respectively. Accordingly, the antenna elements may be considered to belong to different antenna element groups wherein the elements of each group are
5 exposed to similar patterns of the polarization rotation module in their field of view (e.g. each group includes antenna elements of one or more of the superimposed arrays, which are laterally shifted from one another by an integer number of unit cell periods A and B).

It should also be noted that according to some embodiments of the present
10 invention, the polarization rotator module **100** or one or more of its polarizer layers **PL_k** may be configured as an integrated structure. For example, the polarizer layers **PL_k** may be formed on a dielectric substrate/layer with a plurality of continuous conductive line regions **CL_k** printed on the dielectric substrate/layer. According to some embodiments of the present invention, the polarization rotator includes one or more spacer layers
15 arranged in between consecutive polarizer layers **PL_k** that are formed on the dielectric substrate. For example according to some embodiments of the present invention, the dielectric substrate on which the polarizer layers **PL_k** are implemented may include ceramic material, and/or glass-reinforced epoxy laminate materials, such as FR-4. The spacer layers located between adjacent polarizer layers **PL_k** may include structural foam
20 materials such as ROHACELL®. It should be understood that according to some embodiments of the present invention all of the layers of the polarization rotator may be implemented integrally by the integrated structure. Alternatively or additionally, one or more of the polarizer layers, or all of the polarizer layers may be implemented as separate structures and may be fabricated by any suitable technology (e.g. utilizing an
25 integrated structure fabrication technology and/or any other suitable fabrication technology).

In some embodiments, the antenna array **310** may also be configured as an integrated structure, printed on a substrate. To this end the antenna array **310** and the polarization rotation module **100** may be integrated together in a single integrated
30 structure including a stack of printed circuit boards including at least one printed circuit layer with the antenna array printed thereon, and one or more printed circuit boards with one or more of said polarizer layers printed thereon.

CLAIMS:

1. A polarization rotator, comprising:

a plurality of polarizer layers stacked along a general direction of radiation propagation through said polarization rotator; each of said plurality of polarizer layers implements a respective continuous wired grid pattern defining a respective extinction axis for extinction of components of said radiation that are polarized along the respective extinction axis when interacting with the respective one of the plurality of polarizer layers; each pair of consecutive polarizer layers of said polarization rotator are arranged such that their respective extinction axes have different orientations, thereby affecting polarization rotation of the radiation interacting with said polarization rotator;

wherein the continuous wire-grid patterns of the plurality of polarizer layers are arranged with specific relative orientations of their respective extinction axes adjusted to define a lateral tiling of a plurality of substantially identical polarization rotation unit cells in said polarization rotator with respective spatial periods A and B along two lateral axes spanning said tiling in the polarization rotator.

2. The polarization rotator according to claim 1, further comprising a number of N polarization rotation layers arranged in said stack and configured for rotating the polarization of said radiation by a predetermined angle α ; and wherein the number N of polarization rotation layers is selected such that the polarization rotator is operable in a desired operational wavelength bandwidth $\Delta\lambda$.

3. The polarization rotator according to claim 2 wherein a ratio between said predetermined spatial periods, A and B , of the tiling of the substantially identical polarization rotation unit cells along said two lateral axes respectively is given by $A/B = \tan(\alpha)/(N-1)$.

4. The polarization rotator according to claim 2 wherein the plurality of polarizer layers in the stack are configured such that the extinction axes thereof are oriented with orientation angles $\alpha_k = \tan^{-1}((k-1)A/B)$ where k indicates the location of the polarizer layer in the stack.

5. The polarization rotator according to claim 1 wherein continuous wire-grid patterns of the polarizer layers are formed with corresponding respective pitches d_k selected such that said continuous wire-grid patterns are periodic along a certain lateral axis with spatial periodicity $N*d$, where N is an integer number and d is a predetermined value associated with a nominal pitch distance.
6. The polarization rotator according to claim 5 wherein said predetermined respective spatial period A of the unit cells along said certain lateral axis is given by $A = N*d$.
7. The polarization rotator according to claim 5 wherein said respective pitches d_k of the continuous wire-grid patterns of polarizer layers satisfy $d_k = d*N_k*\cos(\alpha_k)$ where N_k is an integer or a rational number associated with each polarizer layer k respectively, and α_k is the orientation of the respective polarizer layer k .
8. The polarization rotator according to claim 7 wherein said respective pitches d_k of the continuous wire-grid patterns of polarizer layers satisfy $d_k = d*\cos(\alpha_k)$.
9. The polarization rotator according to claim 1 wherein the continuous wire-grid pattern of each polarizer layer is formed as an arrangement of a plurality of continuous conductive line regions spaced apart from one another by a distance of less than a nominal wavelength λ of the radiation which is to be polarized and oriented along the extinction axis of the polarizer layer.
10. The polarization rotator according to claim 9 wherein at least some of said polarizer layers comprise a dielectric substrate with said plurality of continuous conductive line regions printed on said dielectric substrate.
11. The polarization rotator according to claim 10, further comprising one or more spacer layers arranged in between at least two of said polarizer layers.
12. The polarization rotator according to claim 11 wherein said dielectric substrate comprises at least one of ceramic or glass-reinforced epoxy laminate materials, said spacer layer comprises structural foam, and the conductive line regions of at least one layer of said polarizer layers are formed utilizing conductive wires arranged in its respective polarizer layer.

13. A radiation module, comprising:

an array of elements being receiving, transmitting, or transceiving elements and a polarization rotator configured according to claim 1;

wherein said array of elements are arranged in a plane substantially parallel to the tiling of the plurality of the polarization rotation unit cells; and

wherein said array of elements are arranged along each of said two lateral axes with respective spatial periodicities A' and B' that are, respectively, integer multiples of the predetermined spatial periods A and B of the polarization rotation unit cells, such that fields of view of said antenna elements are exposed to substantially similar wire-grid patterns of the polarization rotator's layers.

14. The radiation module according to claim 13 being an antenna array and said receiving, transmitting, or transceiving elements are antennas; and wherein each of the receiving, transmitting, or transceiving elements is associated with one or more of said polarization rotator unit cells covering its field of view.