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(54) **Title:** RADIATION UNIT

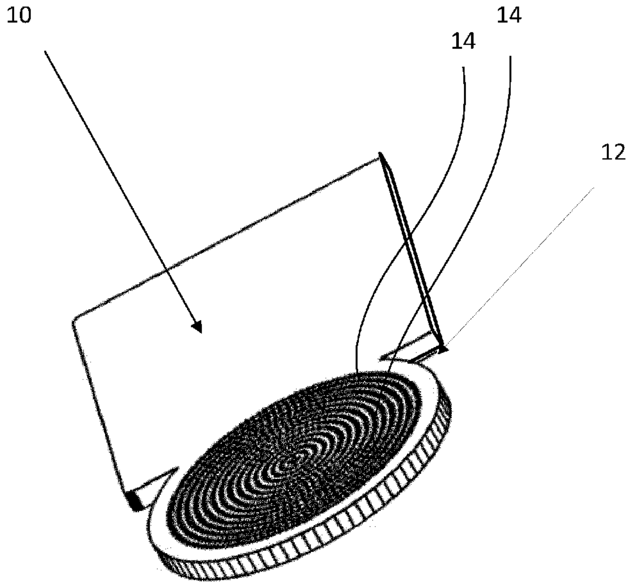

Fig. 1

(57) **Abstract:** The invention refers to a radiation unit comprising a lens (10) having a dielectric refractive lens body (12) that transfers electromagnetic waves. The invention is characterized in that the dielectric refractive lens body (12) has a first relative permittivity ε_{centre} in the center and a second relative permittivity $\varepsilon_{peripheral\ edge}$ in the edge region of the lens, where the first relative permittivity ε_{centre} and the second relativepermittivity $\varepsilon_{peripheral\ edge}$ are related by the relation $\varepsilon_{centre} = 1{,}42 \sqrt{\varepsilon_{peripheral\ edge}} + 0{,}58$, with a tolerance of 0,2, where $|\varepsilon_{peripheral\ edge} - \varepsilon_{centre}| > 0{,}1$ and $\varepsilon_{peripheral\ edge} > 1{,}5$.

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[Continued on next page]

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Radiation Unit

The invention refers to a radiation unit according to the preamble of claim 1.

It is known for example from US 2014 0176 377 A1 that a lens can be made of a solid dielectric material where holes are drilled into the material to impact the refractive index.

The material of the center of the lens has a relative permittivity of 2,04, where the outermost peripheral ring has a relative permittivity of 1,25. The shown lens has a relative permittivity at its edge of less than 1,5 and the deviation from center to edge differs by almost 0,02 from the given rule. There is at least one waveguide coupled to the lens in a way that electromagnetic radiation is transferred from the waveguide to the lens.

The cross-sectional size of the waveguide is inversely proportional to the square root of the dielectric permittivity of the material with which the waveguide is filled. By using a uniform material for coupling between the waveguide and the lens, the permittivity of the lens' material can be directly linked to the permittivity of the material the waveguide is filled with.

It is an object of the invention to use a plurality of waveguides attached to a single lens to obtain an improved resolution and good focusing properties of the lens.

The object is solved by the characterizing features of claim 1 together with the preamble of claim 1.

The subclaims are advantageous embodiments of the invention.

As commonly known in the prior art, the dielectric refractive lens body has a first relative permittivity ε_{centre} in the center and a second relative permittivity $\varepsilon_{peripheral\ edge}$ in the edge region of the lens.

According to the invention, the permittivity is distributed over the lens body in a way that the first relative permittivity ε_{centre} and the second relative permittivity $\varepsilon_{peripheral\ edge}$ fulfill the relation:

$\varepsilon_{centre} = 1,42 \sqrt{\varepsilon_{peripheral\ edge}} + 0,58$, allowing a tolerance band of 0,2, where $|\varepsilon_{peripheral\ edge} - \varepsilon_{centre}| > 0,1$ and $\varepsilon_{peripheral\ edge} > 1,5$.

Due to the tolerance band, the value of ε_{centre} fulfils the relation: $1,42 \sqrt{\varepsilon_{peripheral\ edge}} + 0,78 > \varepsilon_{centre} > 1,42 \sqrt{\varepsilon_{peripheral\ edge}} + 0,38$.

The edge permittivity above 1,5 allows for the coupling of a waveguide that is filled with a material having a relatively high relative permittivity, wherein the relative permittivity is preferably above 2,5 more preferably above 3, thus allowing for waveguides with a small cross-section. If the material according to the prior art were used, the increase of the edge permittivity would lead to a distribution of the relative permittivity inside the lens with which the focusing properties of the beams and, therefore, the gain would be reduced.

By applying the above relation, the lens provides a radiation unit that comprises a higher gain than a lens body with relative permittivity distribution significantly outside the relation of $\varepsilon_{centre} = 1,42 \sqrt{\varepsilon_{peripheral\ edge}} + 0,58$ for a chosen $\varepsilon_{peripheral\ edge}$.

According to this relation, in some cases the second relative permittivity $\varepsilon_{peripheral\ edge}$ is smaller than the first relative permittivity ε_{centre} at the center, while in other cases it is the opposite.

It is the idea of the invention that the dielectric permittivity in the lens’s edge region in transition to an attached waveguide is increased to match a relative permittivity of a substrate integrated waveguide whose relative permittivity is higher than 1,5 so that the reflections at their interface are kept low. As a result, a very good coupling from the lens to the waveguide is achieved so that losses are reduced, thereby achieving better radiation efficiency and hence power consumption can be reduced.

Due to the distribution of the dielectric permittivity according to the invention, the focusing properties of a classical Luneburg lens can almost be achieved with an $\varepsilon_{peripheral\ edge} > 1,5$. Accordingly, an intrinsic connection to an attached waveguide can be achieved where the dielectric material within the waveguide has a permittivity that is higher or close to that of the $\varepsilon_{peripheral\ edge}$.

By increasing or decreasing the permittivity from $\varepsilon_{\text{peripheral edge}}$ to $\varepsilon_{\text{centre}}$, the focusing properties of the lens according to the invention can be achieved that are close to the focusing properties of a classical Luneburg lens.

The dielectric permittivity distribution over the lens in its radial extension follows a square evolution. The radial position r is an element between [0,1], particularly the normalized radius of a sphere or a cylinder, where each point or position having a radial coordinate r has the relative permittivity following the relation:

$$\varepsilon_r (r)= \varepsilon_{\text{centre}} – (\varepsilon_{\text{centre}} - \varepsilon_{\text{peripheral edge}}) r^2.$$

Accordingly, for a given $\varepsilon_{\text{peripheral edge}}$ an $\varepsilon_{\text{centre}}$ can be chosen that guarantees an optimal gain for the lens.

In a preferred embodiment, the distribution is staggered. This can result in a ring-like distribution, where, in particular, the rings are concentrically arranged. In a further preferred embodiment, the width of a ring is between 1/10th and 1/15th of the lens's radius.

One possible way to implement a staggered distribution is to introduce holes in the different rings constituting the lens. In each ring, the effective/equivalent dielectric permittivity is assumed to be the weighted average between that of the dielectric body $\varepsilon_{\text{dielectricBody}}$ and that of the material constituting the holes $\varepsilon_{\text{holes}}$ (anything, in particular air), where the weight given to both quantities is proportional to the percentage of each material in the ring:

$$\varepsilon_{\text{ring}} = (V_{\text{holes}}/V_{\text{ring}})\ \varepsilon_{\text{holes}} + ((V_{\text{ring}}-V_{\text{holes}})/V_{\text{ring}})\ \varepsilon_{\text{dielectricBody}}$$

$$\varepsilon_{\text{ring}} = (\text{\% of holes material in the ring})\ \varepsilon_{\text{holes}} + (\text{\% of dielectric body in the ring})\ \varepsilon_{\text{dielectricBody}}$$

Another possible implementation is a randomized distribution of holes, which does not follow predefined rings/zones. In that case, the effective dielectric permittivity at a given point is considered to be the weighted average between that of the dielectric body $\varepsilon_{\text{dielectric\_body}}$ and that of the material constituting the holes $\varepsilon_{\text{holes}}$ (anything, in particular air), where the weight given to both quantities is proportional to the percentage of each material in a cylindrical zone of a cylindrical lens (with an axis aligned with the axis of the cylindrical lens) of radius equal to a tenth of the lens radius, centered around the given point, and of a thickness covering exclusively the cylindrical lens thickness/height. A cylindrical lens can shape a fan shaped beam that allows for evaluating an echo along a band shaped section. A combination of two such lenses for transmitting and receiving can produce a grid.

Another possible implementation is a randomized distribution of holes, which does not follow predefined rings/zones. In that case, the effective dielectric permittivity at a given point is considered to be the weighted average between that of the dielectric body $\varepsilon_{dielectricBody}$ and that of the material constituting the holes ε_{holes} (anything, in particular air), where the weight given to both quantities is proportional to the percentage of each material in a spherical zone (in the case of a spherical lens) of a radius equal to a tenth of the lens radius, centered around the given point.

Further advantages, features and potential applications of the present invention may be gathered from the description which follows, in conjunction with the embodiments illustrated in the drawings.

Throughout the description, the claims and the drawings, those terms and associated reference signs will be used as are notable from the enclosed list of reference signs. In the drawings is shown:

Fig. 1 a perspective view of a lens according to the invention;

Fig. 2 a curve of the relation $\varepsilon_{peripheral\ edge}$ to ε_{centre}; and

Fig. 3 a graphic illustration of the function $\varepsilon_r(r)$ for several ε_{centre} / ε_{edge} combinations.

Fig. 1 shows a perspective view of a lens 10 according to the invention. The lens 10 of Fig. 1 can be part of a radiation unit. The lens 10 comprises a cylindrical dielectric body 12 that is covered by a metal layer on the top and the bottom side of the dielectric body. The lens 10 furthermore comprises holes 14, shown in black, that are drilled into the dielectric body 12. To ensure the effective/equivalent dielectric permittivity at the lens peripheral edge and at the lens's center the shape and the distribution of the holes 14 are chosen to meet the criteria $\varepsilon_{centre} = 1{,}42\ \sqrt{\varepsilon_{peripheral\ edge}} + 0{,}58$, having a tolerance band of 0,2. , where furthermore $|\varepsilon_{peripheral\ edge} - \varepsilon_{centre}| > 0{,}1$ and $\varepsilon_{peripheral\ edge} > 1{,}5$. The holes 14 do not necessarily need to have a circular cross-section. Accordingly, the value of ε_{centre} fulfils the relation: $1{,}42\ \sqrt{\varepsilon_{peripheral\ edge}} + 0{,}78 > \varepsilon_{centre} > 1{,}42\ \sqrt{\varepsilon_{peripheral\ edge}} + 0{,}38$.

The dielectric permittivity distribution over the lens body 12 in its radial extension basically follows the function $\varepsilon_r\,(r) = \varepsilon_{centre} - (\varepsilon_{centre} - \varepsilon_{peripheral\ edge})\, r^2 \mid r \in [0,1]$, where r is the normalized radial coordinate.

The distribution is staggered which leads to a ring like distribution of the dielectric permittivity, where the width of a ring is between 1/10th and 1/15th of the radius. In each ring, the effective/equivalent dielectric permittivity is assumed to be the weighted average between that of the dielectric body $\varepsilon_{dielectricBody}$ and that of the material constituting the holes ε_{holes} (anything, in particular air), where the weight given to both quantities is proportional to the percentage of each material in the ring:

$$\varepsilon_{ring} = (V_{holes}/V_{ring})\, \varepsilon_{holes} + ((V_{ring} - V_{holes})/V_{ring})\, \varepsilon_{dielectricBody}$$

$$\varepsilon_{ring} = (\%\text{ of holes material in the ring})\, \varepsilon_{holes} + (\%\text{ of dielectric body in the ring})\, \varepsilon_{dielectricBody}$$

In this case, each ring comprises an equal width of 1mm. The innermost zone, naturally, is a circle and not a ring.

Fig. 2 shows a graph $\varepsilon_{centre} = 1.42\, \sqrt{\varepsilon_{peripheral\ edge}} + 0.58$. The graph shows the optimal relation between a given edge permittivity $\varepsilon_{peripheral\ edge}$ and the center permittivity ε_{centre}.

Fig. 3 shows the relation of $\varepsilon_r(r) = \varepsilon_{centre} - (\varepsilon_{centre} - \varepsilon_{edge})\, r^2$ for several ε_{centre} / ε_{edge} combinations.

In this case, the graphs show a continuous distribution, but the distribution could also be implemented by zones, preferably of equal width, where the zones are defined in a way to approximately match the continuous distribution.

In this case the lowermost curve has a value of ε_{edge} which is close to that of air having a value of 1,5, where the ε_{centre} = 2,3.

The distribution that is preferably used in this application, corresponds to an approximation of the shown ideal curve 30 which relates to a combination ε_{centre} = 2,9 and ε_{edge} = 2,6.

Having lenses correlating with this distribution, a lens can be chosen perfectly matched for the intended application, thereby providing optimal gain.

List of reference signs

10	lens
12	dielectric lens body
14	holes
30	curve

Claims

1. Radiation unit comprising a lens (10) having a dielectric refractive lens body (12) that transfers electromagnetic waves, **characterized in that** the dielectric refractive lens body (12) has a first relative permittivity ε_{centre} in the center and a second relative permittivity $\varepsilon_{peripheral\ edge}$ in the edge region of the lens, where the first relative permittivity ε_{centre} and the second relative permittivity $\varepsilon_{peripheral\ edge}$ are related by the relation $\varepsilon_{centre} = 1{,}42\ \sqrt{\varepsilon_{peripheral\ edge}} + 0{,}58$, with a tolerance of 0,2, where $|\varepsilon_{peripheral\ edge} - \varepsilon_{centre}| > 0{,}1$ and $\varepsilon_{peripheral\ edge} > 1{,}5$.

2. Radiation unit according to claim 1, **characterized in that** the lens (10) comprises at least two zones, where each zone comprises a point/position with a radial coordinate r corresponding to a relative permittivity value $\varepsilon_r(r)$, where $\varepsilon_r(r) = \varepsilon_{centre} – (\varepsilon_{centre} - \varepsilon_{peripheral\ edge})r^2$.

3. Radiation unit according to claim 1 or 2, **characterized in that** the lens (10) is a gradient index lens whose permittivity successively increases or decreases from the first relative permittivity ε_{centre} to the second relative permittivity $\varepsilon_{peripheral\ edge}$.

4. Radiation unit according to claim 3, **characterized in that** the lens (10) is a generalized Luneburg lens.

5. Radiation unit according to one of the claims 1 to 3, **characterized in that** that the dielectric refractive lens body (12) is of a solid dielectric material where the body comprises holes (14) to provide said permittivity distribution.

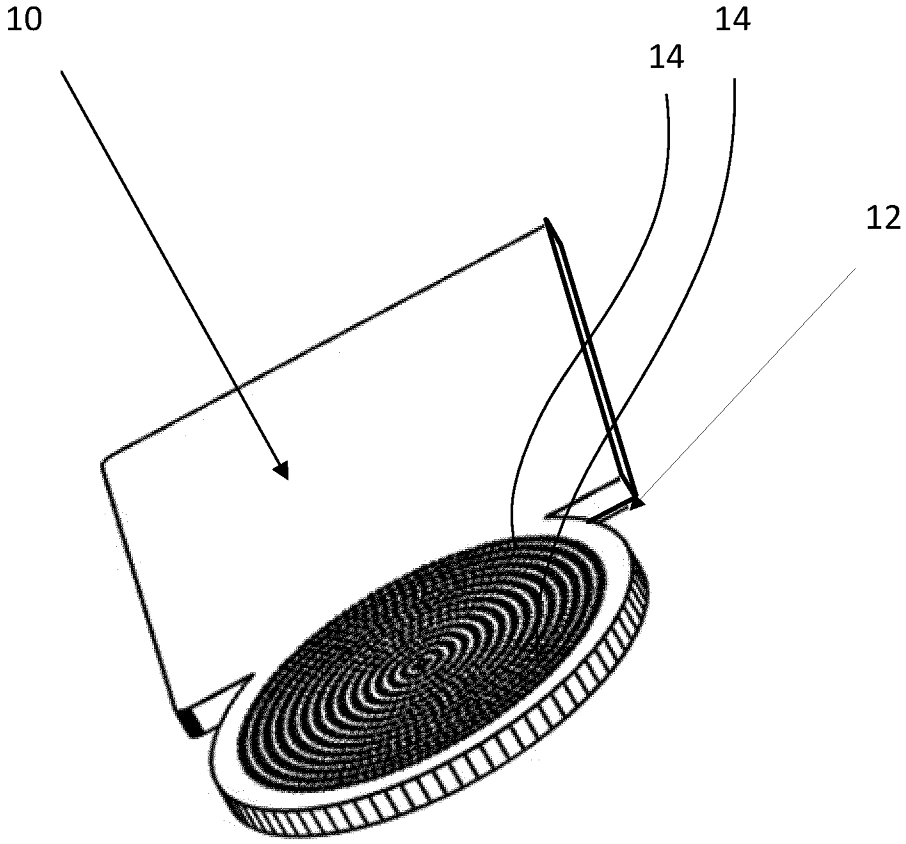

Fig. 1

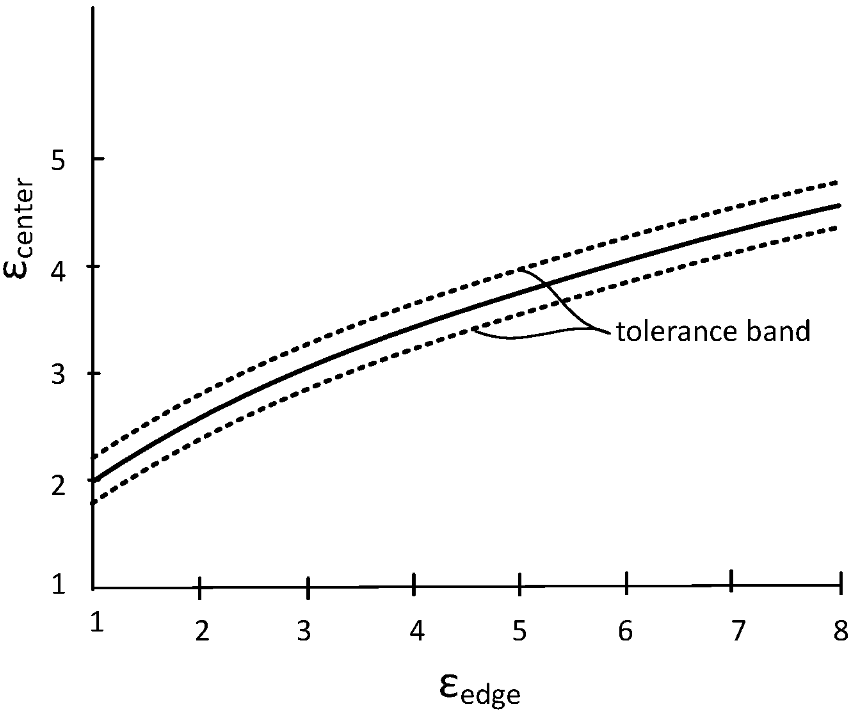
ε_{center}
5
4
3
2
1
1
2
3
4
5
6
7
8
ε_{edge}
tolerance band

Fig. 2

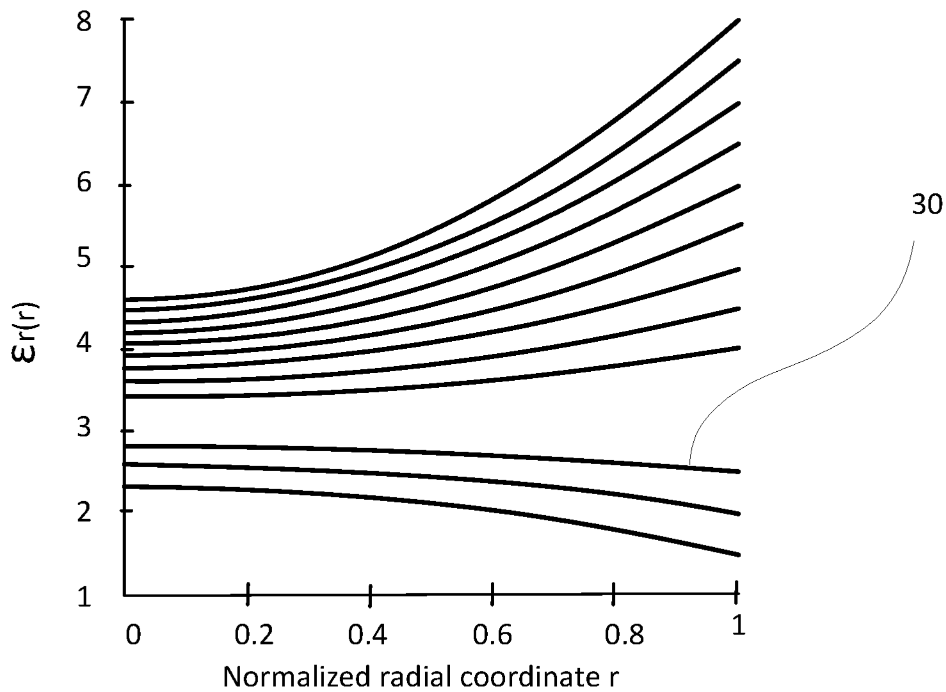
8
7
6
5
4
3
2
1
$\varepsilon_r(r)$
30
0
0.2
0.4
0.6
0.8
1
Normalized radial coordinate r

Fig. 3

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2024/051917

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01Q15/08 H01Q19/06
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H01Q

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	CN 114 583 464 A (CHENGDU FREQUENCY MICROELECTRONIC LTD COMPANY) 3 June 2022 (2022-06-03) paragraph [0038] - paragraph [0064]; figures 1,2 -----	1-5
A	ZHANG SHIYU ET AL: "3D-printed planar graded index lenses", IET MICROWAVES, ANTENNAS & PROPAGATION, THE INSTITUTION OF ENGINEERING AND TECHNOLOGY, UNITED KINGDOM, vol. 10, no. 13, 22 October 2016 (2016-10-22), pages 1411-1419, XP006058859, ISSN: 1751-8725, DOI: 10.1049/IET-MAP.2016.0013 page 1411 - page 1419; figure 1 ----- -/--	1-5

[x] Further documents are listed in the continuation of Box C.

[x] See patent family annex.

* Special categories of cited documents :

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Date of the actual completion of the international search	Date of mailing of the international search report
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Form PCT/ISA/210 (second sheet) (April 2005)

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	LIU PENGFEI ET AL: "A Novel E-plane-Focused Cylindrical Luneburg Lens Loaded With Metal Grids for Sidelobe Level Reduction", IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, IEEE, USA, vol. 68, no. 2, 28 September 2019 (2019-09-28), pages 736-744, XP011769790, ISSN: 0018-926X, DOI: 10.1109/TAP.2019.2943438 [retrieved on 2020-01-31] page 736 - page 744; figures 1,2 -----	1-5

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2024/051917

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
CN 114583464 A	03-06-2022	NONE	