Sensor and Simulation Notes

Note 387

18 September 1995

Steerable Lens Surface for Use with the IRA Class of Antennas

Carl E. Baum
Phillips Laboratory

Abstract

One can use a lens to scan (steer) the beam from an impulse radiating antenna (IRA). For high-power applications the IRA may be located in the high-dielectric-strength lens medium. By segmenting the lens such that the lens parts can slide along the common interface while remaining in contact, the direction of the emerging beam can be varied while the IRA and its emerging beam remain spatially fixed. The appropriate surfaces for dividing the lens with all resulting dielectric lens volumes having the same permittivity are spheres, circular cylinders (or other bodies of revolution), and planes. Using liquid dielectric one can also have a bendable lens with a bellows arrangement.

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One can use a lens to scan (steer) the beam from an impulse radiating antenna (IRA). For high-power applications the IRA may be located in the high-dielectric-strength lens medium. By segmenting the lens such that the lens parts can slide along the common interface while remaining in contact, the direction of the emerging beam can be varied while the IRA and its emerging beam remain spatially fixed. The appropriate surfaces for dividing the lens with all resulting dielectric lens volumes having the same permittivity are spheres, circular cylinders (or other bodies of revolution), and planes. Using liquid dielectric one can also have a bendable lens with a bellows arrangement.

1. Introduction

Consider that we have an impulse-radiating antenna (IRA) embedded in a dielectric medium such as plastic or transformer oil. Several examples of such are given in [6] where the IRA is taken as the reflector type. Besides the basic reflector version [1, 5], there is the terminated TEM horn with lens [1, 4], and the array version [2, 3]. All of these have the property of being able to produce a fast-rising temporal plane wave on an aperture plane S_a, this, in turn, producing a narrow impulsive wave in the far field. With $\vec{1}_a$ as the unit outward-pointing unit normal on S_a, let this also be the direction of propagation of the wave transmitted from the antenna.

As indicated in fig. 1.1A a ray path leaving S_a parallel to $\vec{1}_a$ passes through a planar lens surface S_ℓ with no bending provided its outward pointing unit normal $\vec{1}_\ell$ is parallel to $\vec{1}_a$ (or equivalently S_ℓ is parallel to S_a). The lens material has permittivity $\varepsilon_\ell > \varepsilon_0$ (and permittivity μ_0) so that there is some reflection at S_ℓ which though is not included in the present discussion. Note that the external medium outside the lens is taken to have permittivity ε_0 (and permittivity μ_0), appropriate to air and other gasses. However, by replacing ε_0 by another permittivity the results apply to other media as well. The relevant parameter is the relative dielectric constant

$$\varepsilon_r \equiv \frac{\varepsilon_\ell}{\varepsilon_0} \tag{1.1}$$

As in fig. 1.1B, let S_ℓ be inclined an angle ψ_i (the angle of incidence) with respect to S_a where

$$\vec{1}_a \cdot \vec{1}_\ell = \cos(\psi_i) \tag{1.2}$$

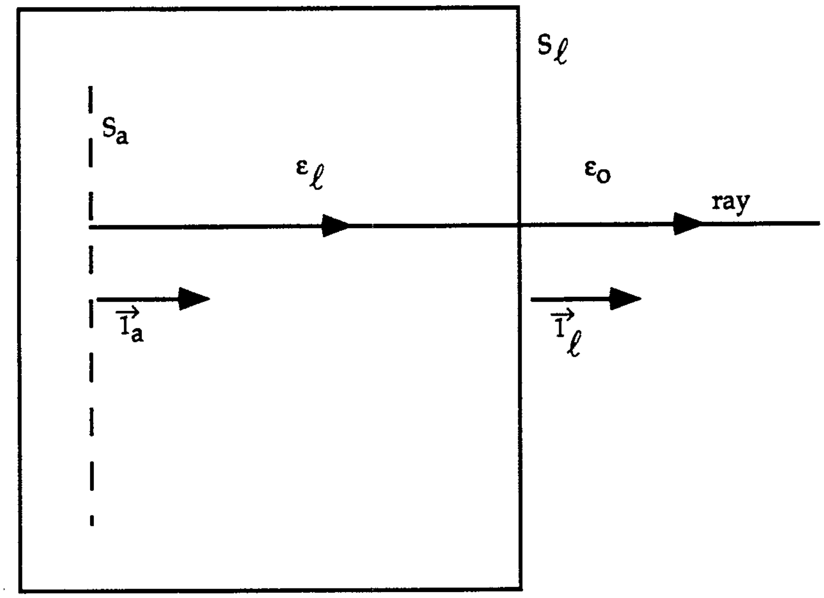
With ψ_t as the angle of transmission (angle of the ray with respect to $\vec{1}_\ell$) we have the usual formula

$$\sin(\psi_t) = \sqrt{\varepsilon_r}\ \sin(\psi_i) \tag{1.3}$$

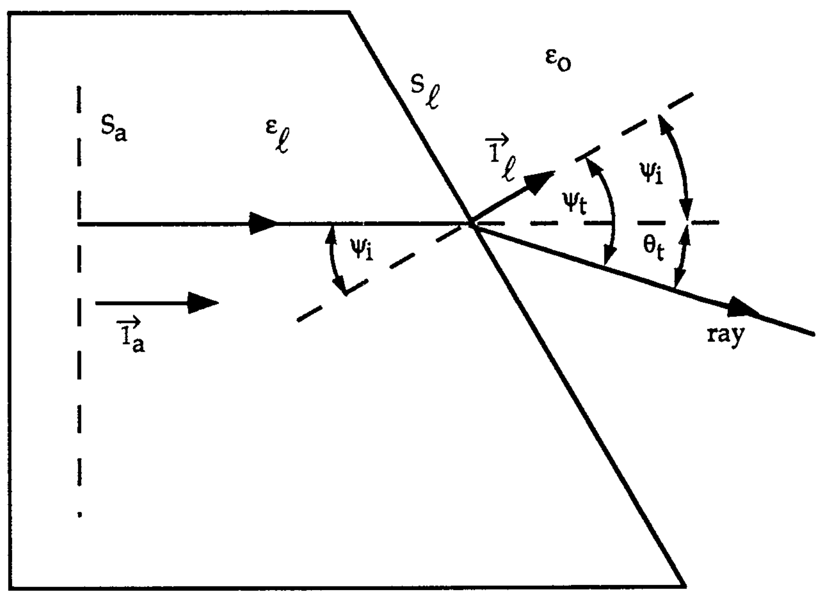
The bend angle θ_t of the ray is just

$$\theta_t = \psi_t - \psi_i = \arcsin\left[\sqrt{\varepsilon_r}\sin(\psi_i)\right] - \psi_i \tag{1.4}$$

This angle is limited by the transmitted ray being parallel to S_ℓ for which ψ_t is $\pi/2$. Assuming transformer oil or polyethylene we have



A. Normal incidence on lens surface: rays straight



B. Oblique incidence on lens surface: rays straight

Fig. 1.1. Lens Surface and Ray Path

$$
\begin{aligned}
\varepsilon_r &= 2.26 \\
\psi_{t_{\max}} &= 90^\circ \\
\psi_{i_{\max}} &\simeq 41.70^\circ \\
\theta_{t_{\max}} &\simeq 48.30^\circ
\end{aligned}
\tag{1.5}
$$

as a limitation on how far one can bend the beam with a single lens surface. One would not like to operate too close to this limit since the effective aperture area outside the lens tends to zero. For small ψ_i we have

$$
\begin{aligned}
\theta_t &= \left[\sqrt{\varepsilon_r} - 1\right]\psi_i + O(\psi_i^3) \text{ as } \psi_i \to 0 \\
&\simeq 0.503\,\psi_i \text{ for transformer oil}
\end{aligned}
\tag{1.6}
$$

Another set of angles of interest are the Brewster angles given by

$$
\begin{aligned}
&\cot(\psi_{iB}) = \tan(\psi_{tB}) = \frac{1}{\sqrt{\varepsilon_r}} \\
&\psi_{iB} + \psi_{tB} = 90^\circ \\
&\psi_{iB} \simeq 33.63^\circ,\ \psi_{tB} \simeq 56.37^\circ,\ \theta_{tB} \simeq 22.73^\circ \text{ (transformer oil)}
\end{aligned}
\tag{1.7}
$$

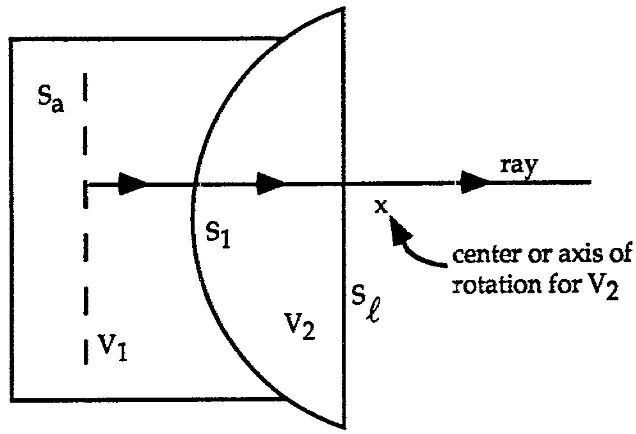
This applies to the case that the incident wave is polarized as an E (or TM) wave with respect to $\vec{1}_\ell$ (or S_ℓ), in which case there is no reflection (i.e., total transmission) at S_ℓ.

While fig. 1.1B shows how the beam is bent, a more difficult problem concerns how to scan the beam, i.e., vary θ_t as well as the azimuthal angle θ (imagining $\vec{1}_a$ as defining the z axis in the usual (r, θ, ϕ) spherical coordinate system). Of course, by moving the entire dielectric region to reorient $\vec{1}_a$ and rotate about this axis one can achieve such a scanning of the beam in two angles. However, let us assume for the present discussion that the region of the dielectric containing S_a and the IRA (e.g., with a paraboloidal reflector) is fixed in space (i.e., fixed relative to some platform such as an airframe, etc.), and that one wishes to still vary θ_t and ϕ_t This may be the case if very high powers are being transmitted such that large pulsers are rigidly connected to the IRA so as to accommodate the large electric fields, especially in the feed region of the antenna. This paper discusses some techniques for accomplishing this beam steering by segmenting the dielectric into two or more regions, the first (immobile) containing the IRA and the others moving with respect to the first to obtain the beam scanning.

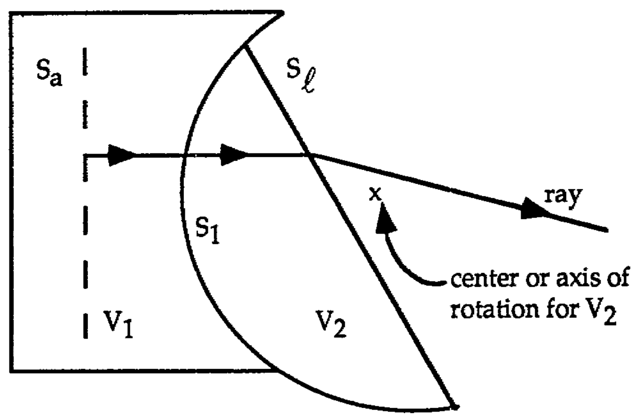
2. Compound Lens: Circular Cylindrical or Spherical Surface

Now divide the dielectric region into two parts labeled V_1 and V_2, separated by surface S_1, as indicated in fig. 2.1. Here and later, all lens volumes (V_1, V_2, and later V_3) have the same permittivity ε_ℓ. Letting V_1 be the portion containing the IRA and thereby immobile with respect to the antenna platform, label this case as a concave lens where S_1 is concave as referenced to V_1. (Of course S_1 is convex when referenced to V_2, the movable part.) For this concave case S_1 can be taken as a portion of a circular cylinder (or a more general body of revolution) with rotation axis on the side of S_1 away from S_a (to the right in figs. 2.1A and B). As a body of revolution with a rotation axis, the beam is scanned along a plane (only one scan angle). For more general scanning one can make S_1 as a portion of a sphere, allowing V_2 to rotate in contact with V_1 at S_1 over two scan angles. (See fig. 2.1C.) In this case, the axis of revolution becomes a center of rotation (the center of the sphere of which S_1 is a part).

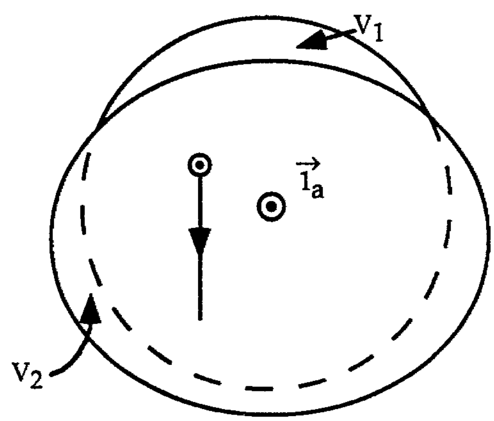
An alternate design approach, labeled convex (S_1 with respect to V_1 again), is illustrated in fig. 2.2. Here the center or axis of revolution is located to the left of S_1 in figs. 2.2A and B. Depending on specifics of some of the dimensions, this point or axis can be on either side of S_a. Again S_1 can be a part of a circular cylinder (single scan angle) or a sphere as in fig. 2.2C (two scan angles).



A. Rays straight (reference position): top or side view

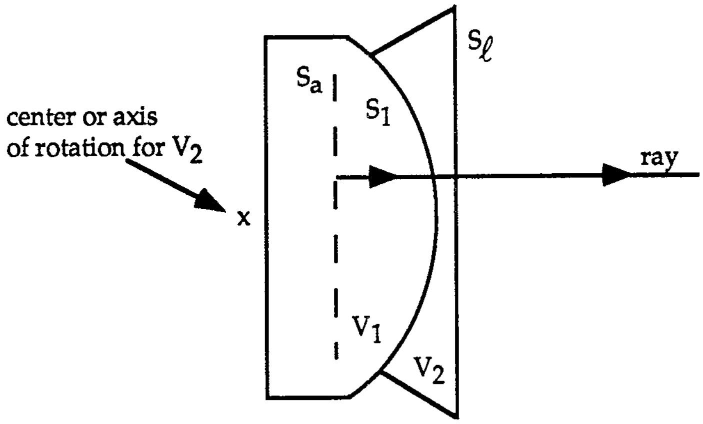


B. Rays bent: sliding contact of two lens parts at S_1

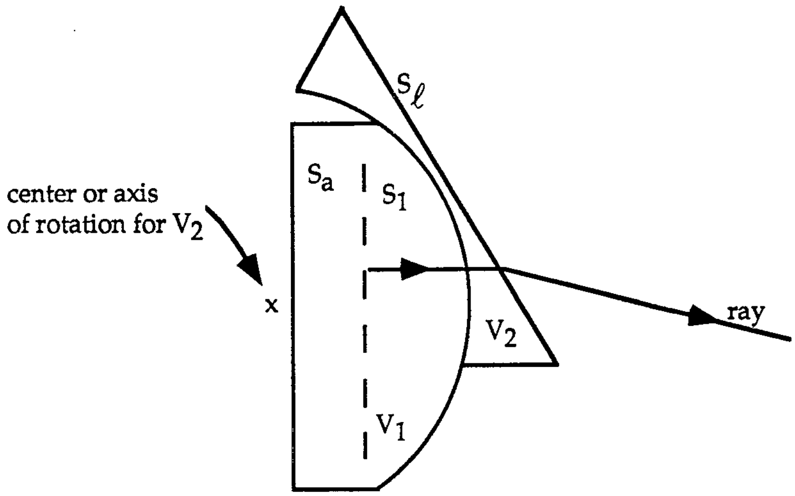


C. Rays bent: front view with S_1 spherical

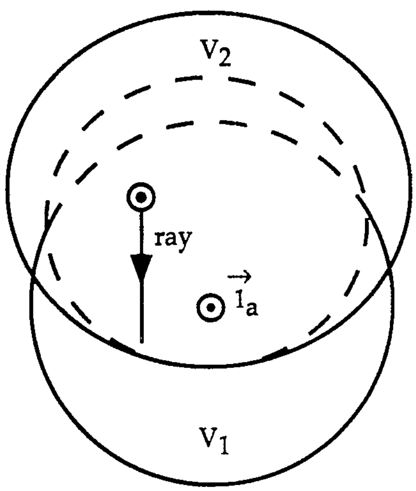
Fig. 2.1. Concave Compound Lens: S_1 Circular Cylindrical or Spherical



A. Rays straight (reference position): top or side view



B. Rays bent: sliding contact of two lens parts at S_1



C. Rays bent: front view with S_1 spherical

Fig. 2.2. Convex Compound Lens: S_1 Circular Cylindrical or Spherical

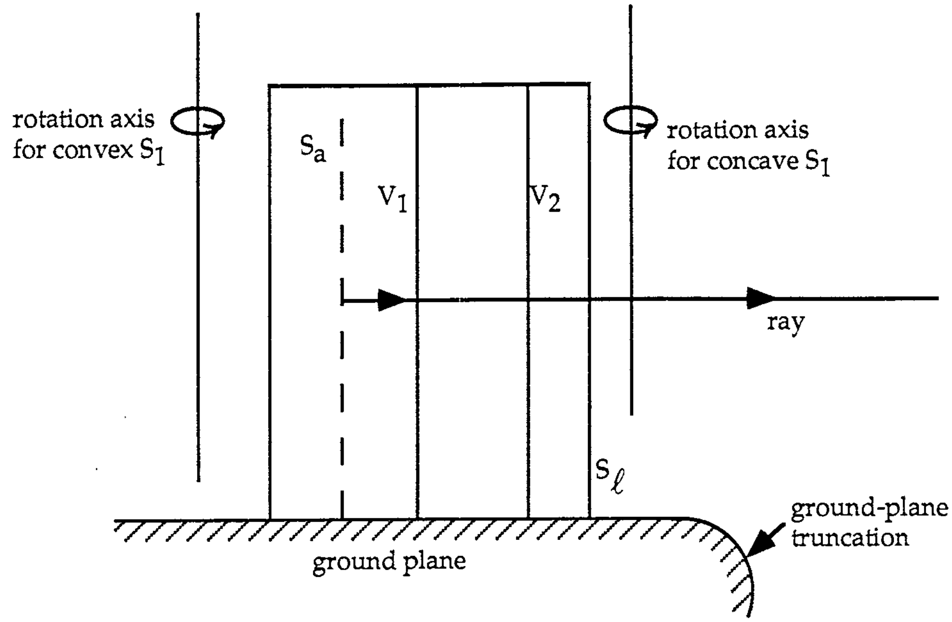
3. Application to Half IRA and Split IRA

As discussed in [4, 5], one can combine a ground plane with an IRA to form a half IRA. This of course constrains the polarization to be perpendicular to the ground plane and the propagation to be parallel to the ground plane. As illustrated in fig. 3.1A, if the ground plane forms a boundary to V_2 as well as V_1, the rotation of V_2 is about an axis perpendicular to the ground plane. This applies to both concave lenses (top view as in figs. 2.1A and B) and convex lenses (top view as in figs. 2.2A and B). Note that for various applications the ground plane is not of infinite extent but can be truncated in various ways.

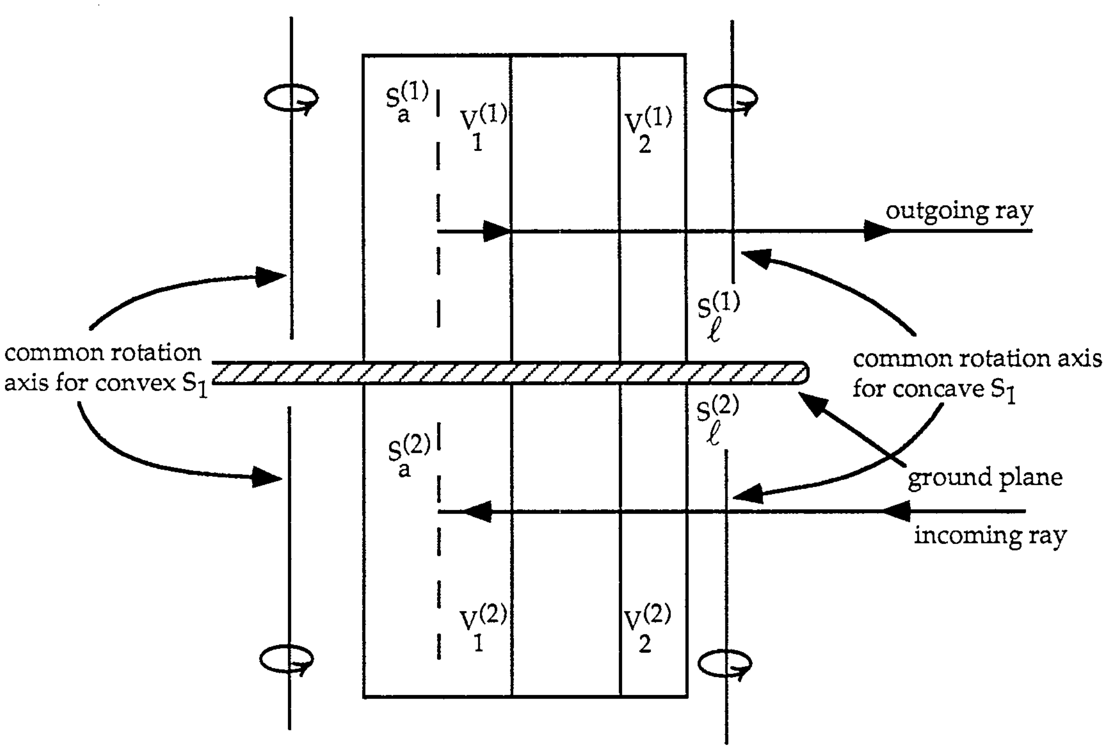
Extending the above concept to the split IRA, we have as in fig. 3.1B. The ground plane is now a divider between two half IRAs, one operating in transmission (say the top one) and the second operating in reception (say the bottom one). The ground plane provides some isolation from direct coupling of signals between the two. For operation as a backscatter radar, the movable parts of the two lenses $V_2^{(1)}$ and $V_2^{(2)}$ (superscripts denoting which of the two IRA/lens systems is meant) need to be rotated together so that both IRAs are focused in the same direction (i.e., to the target at some large distance away). Note that in this form the steerable split IRA scans in only one angle, i.e., parallel to the ground plane.

One can increase the scanning capability of the split IRA by truncating the ground plane such that it does not enter the V_2 region which is now made in one piece as illustrated in fig. 3.2. As such S_1 is continuous on V_2, but if the ground plane is truncated at S1 then V1 is still split into two parts. In this form, note that V_2 is not constrained by the presence of the ground plane, but can move past it as indicated in fig. 3.2. With V_2 all in one piece, then the focusing directions for transmission and reception automatically track together. Now S_1 can be either a part of a circular cylinder (or more general body of revolution) giving one scan angle, or part of a sphere giving two scan angles.

One can shape the truncation of the ground plane separating the two halves of a split IRA in various ways, still keeping it out of V_2 (i.e., within V_1). In particular, one can try to minimize direct coupling of signals from the transmitter to the receiver. For example, one can avoid a straight-line truncation parallel to S_a (perpendicular to $\vec{1}_a$) which would have an edge diffraction which would arrive back on $S_a^{(2)}$ with maximum coherence.

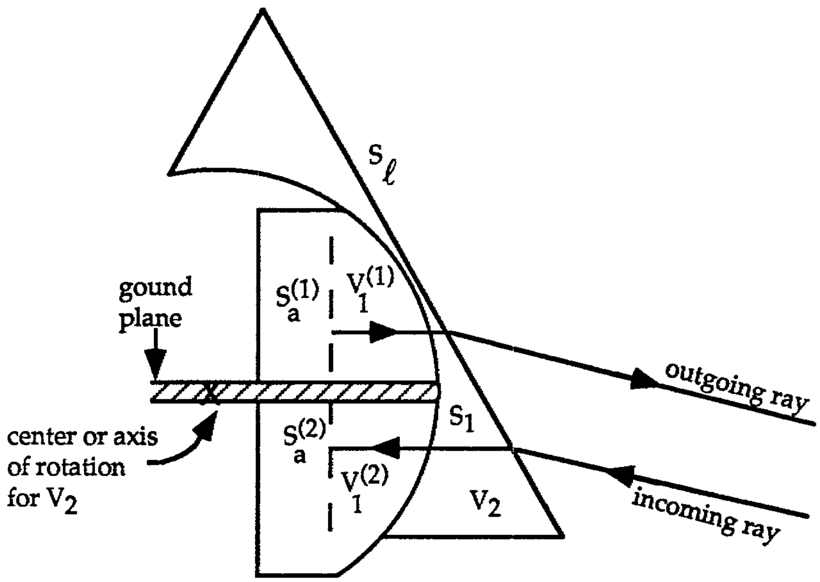


A. Half IRA

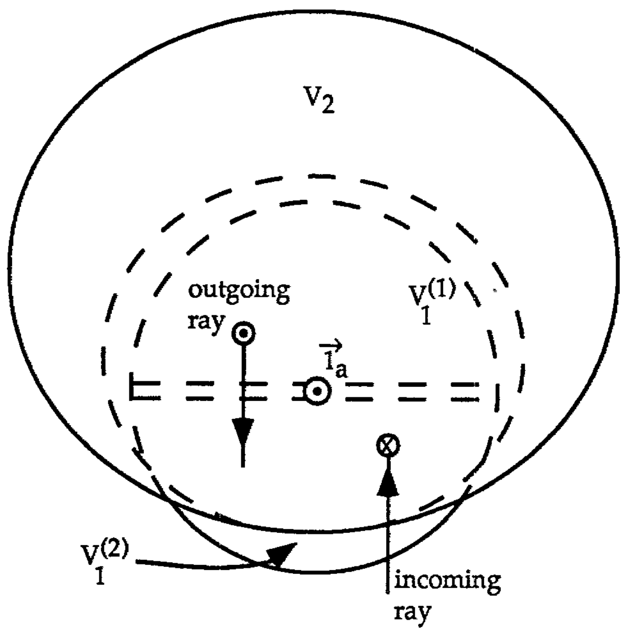


B. Split IRA

Fig. 3.1. Half IRA and Split IRA with Ground Plane Forming a Boundary for the Movable Part of the Lens



A. Side (or top) view



B. Front view with S_1 spherical

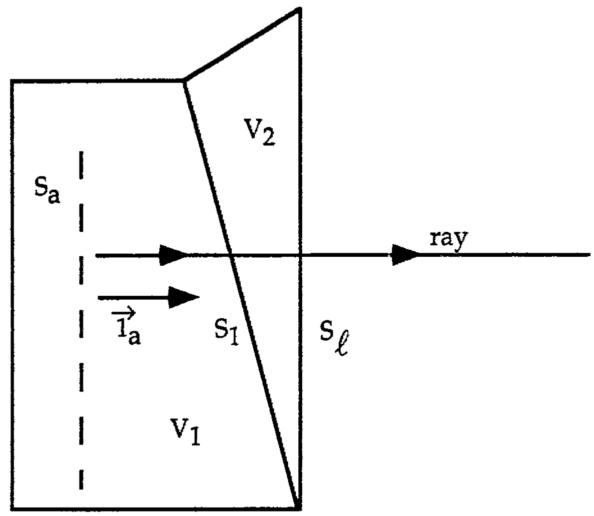
Fig. 3.2. Split IRA with V_2 All in One Piece: Convex Compound Lens

4. Compound Lens: One or Two Planar Surfaces

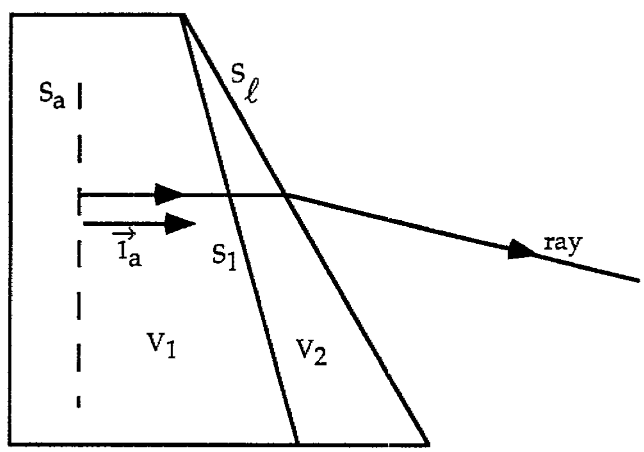
One can also achieve scanning with S_1 as a planar surface as indicated in fig. 4.1. Now V_2 takes the form of a wedge which, when rotated with sliding contact at S_1, gives one angle of scan. However, the beam does not scan parallel to a plane in this configuration. In the illustration S_1 is not perpendicular to $\vec{1}_a$. One can also have a case with S_1 perpendicular to $\vec{1}_a$, in which case the beam scans as a circular cone as V_2 is rotated, this cone being described by varying ϕ_t with constant θ_t. (See fig. 1.1B.)

This can be extended by using two planar surfaces, S_1 and S_2, to divide the lens into three volumes as indicated in fig. 4.2. In this case, letting S_1 be perpendicular to $\vec{1}_a$ the combination of V_2 and V_3 can be rotated about $\vec{1}_a$ to vary ϕ_t for a fixed θ_t. By rotating V_3 with respect to V_2 while maintaining contact on S_2 various values of θ_t are also achieved, thereby giving two scan angles. This configuration of two wedge prisms (V_2 and V_3) is similar to a common optical instrument [7 (Section 2.7)].

This configuration can also be applied to the split IRA as in Section 3. Two scan angles are retained provided the ground plane does not penetrate V_2 or V_3.

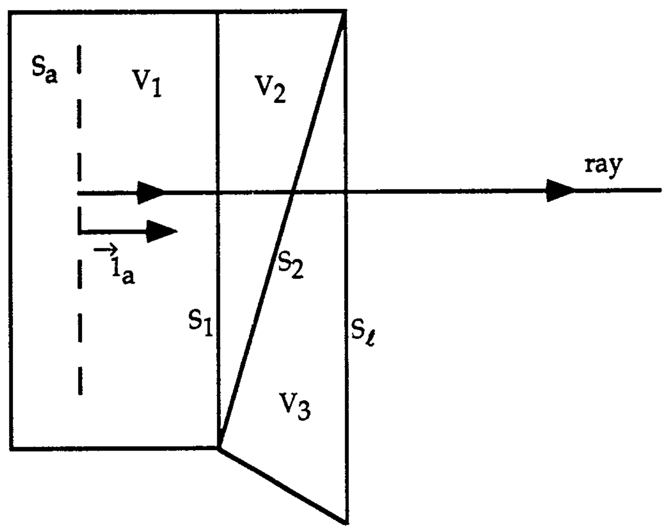


A. Rays straight

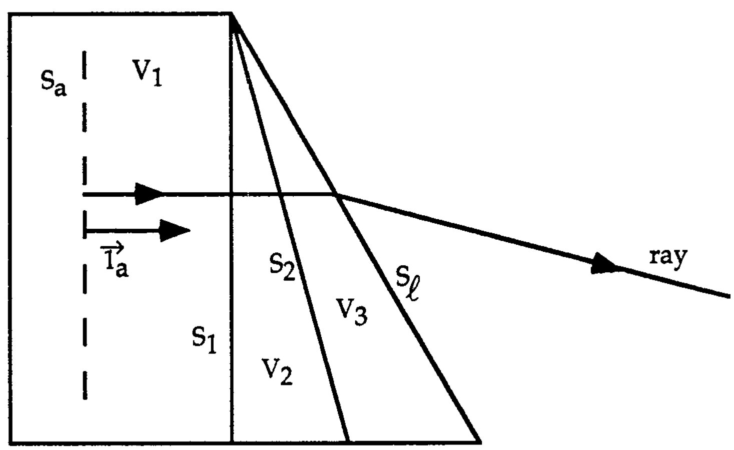


B. Rays bent

Fig. 4.1. Compound Lens: S_1 Planar Surface



A. Rays straight

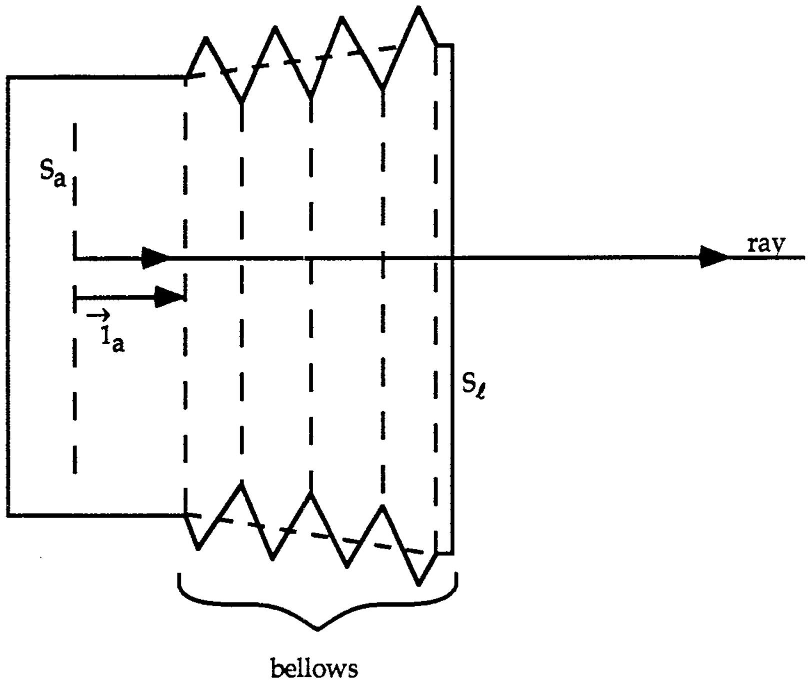


B. Rays bent

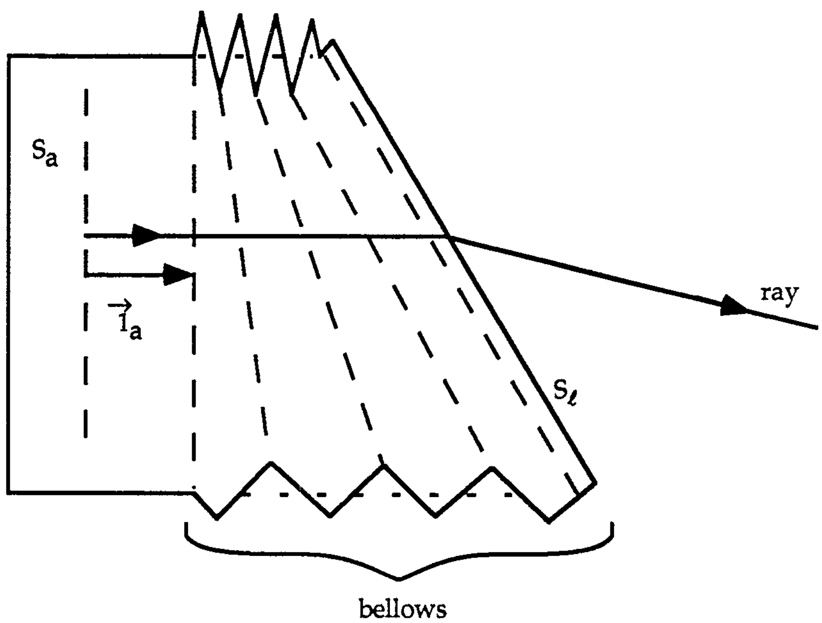
Fig. 4.2. Compound Lens: S_1 and S_2 Planar Surfaces

5. Bendable Lens: Bellows

Returning to fig. 1.1, one might ask if there is some other way to incline S_ℓ in a variable way. In effect, one might like some way to "bend" the lens. If the lens is liquid as in the case of transformer oil, one can do this as illustrated in fig. 5.1. Of course the oil is contained in some solid cover such as polyethylene. The bending is accomplished by means of a bellows which allows certain portions of the cover to contract while others expand (thereby keeping the volume of oil in the lens constant, if desired).



A. Rays straight



B. Rays bent

Fig. 5.1. Liquid Dielectric Lens with Bellows

6. Concluding Remarks

There are then various ways to make dielectric lenses to scan the beam from an IRA. The emphasis here is for the case of transmitting extremely high powers. While the examples of segmented lenses here have assumed the same permittivity for all lens volumes (for simplicity), this need not be the case. The various V_n can have different permittivities if the dividing boundaries are planes. Note that outside the lens need not be air, but at least in part some high-dielectric-strength gas such as SF_6. The various types of lenses with movable surfaces illustrated here are not exhaustive as one can combine these in various ways to obtain more elaborate designs.

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