United States Patent [19]

Fugitt et al.

[11] **3,709,580**

[45] **Jan. 9, 1973**

[54] **EXTENDED RANGE POLARIZATION TARGET**

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[73] Assignee: **The United States of America as represented by the Secretary of the Navy**

[22] Filed: **March 18, 1971**

[21] Appl. No.: **125,665**

[52] **U.S. Cl.** **350/157**, 350/105, 350/152, 350/156

[51] **Int. Cl.**.....**G02b 5/30**

[58] **Field of Search**.....350/147, 152, 156, 157, 102, 350/105, 109

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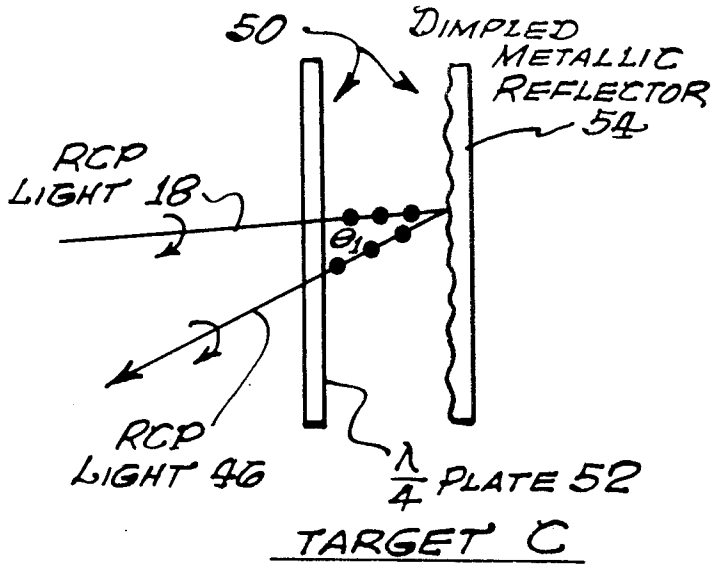
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[57] **ABSTRACT**

A reflector, particularly useful for underwater use, comprising a base material having angled surfaces for retro-reflecting an incident beam of light back substantially parallel to the incident beam, and means for polarizing the reflected beam into the same circular polarization handedness as the incident beam.

2 Claims, 14 Drawing Figures



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SHEET 1 OF 4

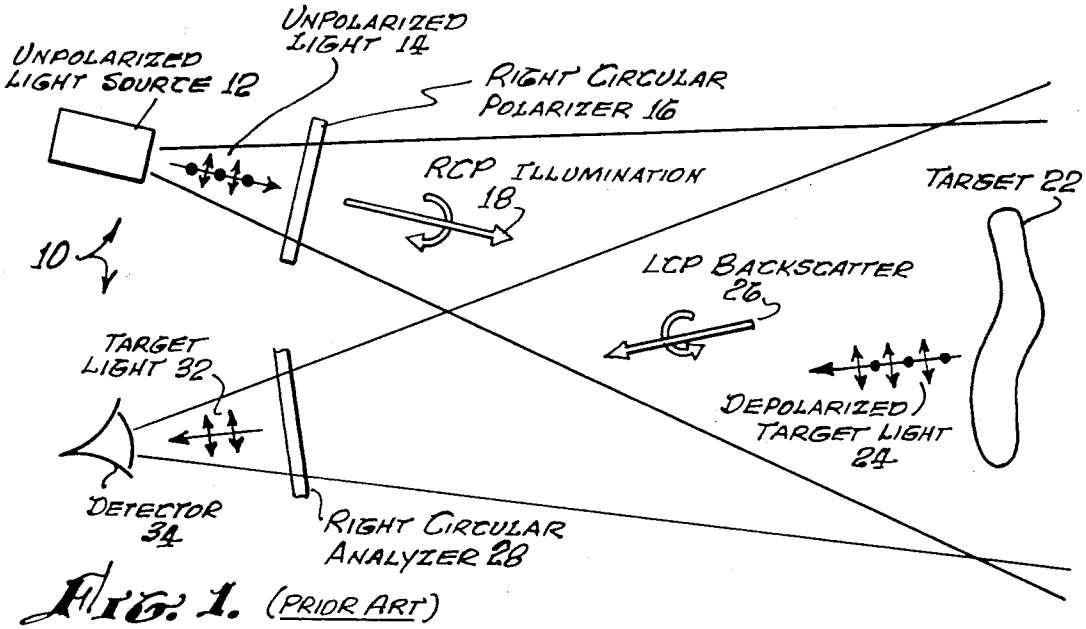


FIG. 1. (PRIOR ART)

CIRCULAR POLARIZATION TECHNIQUE FOR ELIMINATION OF BACKSCATTER.

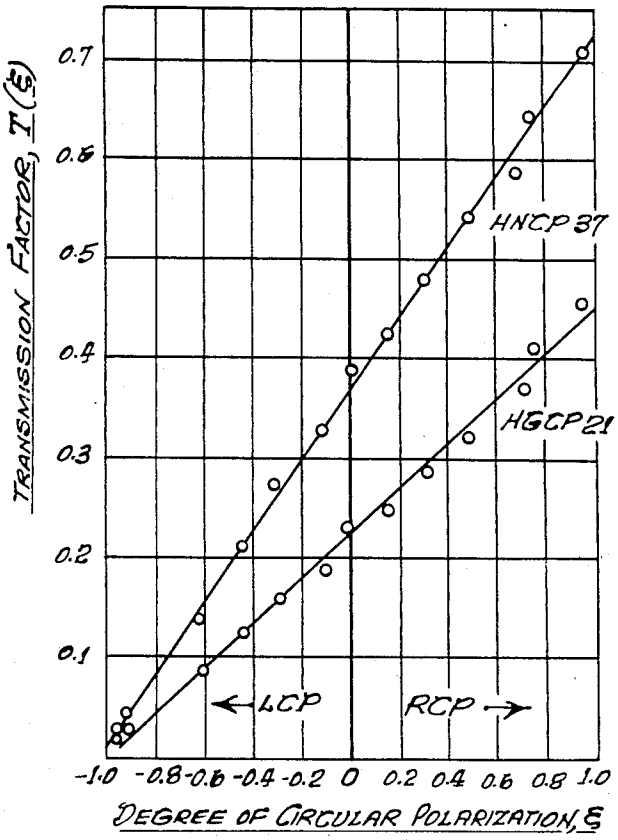


FIG. 4.

TRANSMISSION FACTOR OF CIRCULAR POLARIZATION ANALYZERS.

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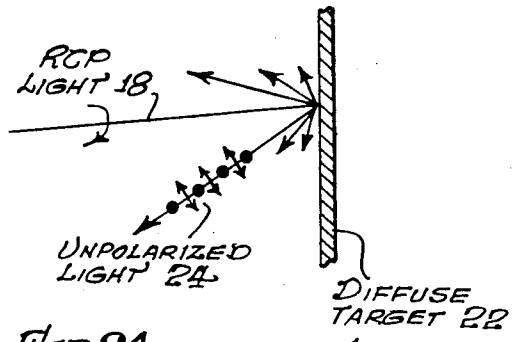


FIG. 2A. TARGET A

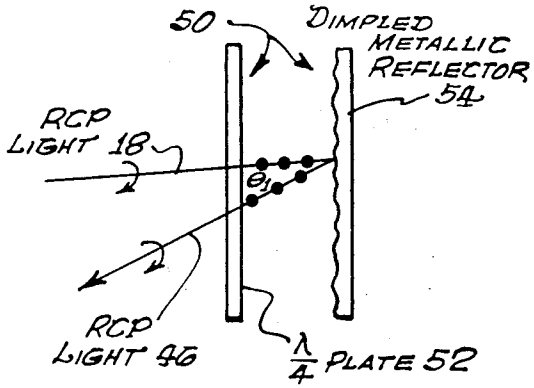


FIG. 2C. TARGET C

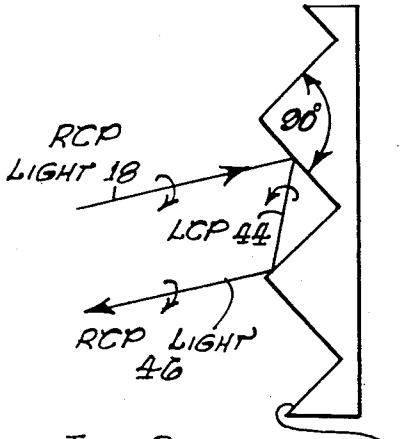


FIG. 2B. TARGET B

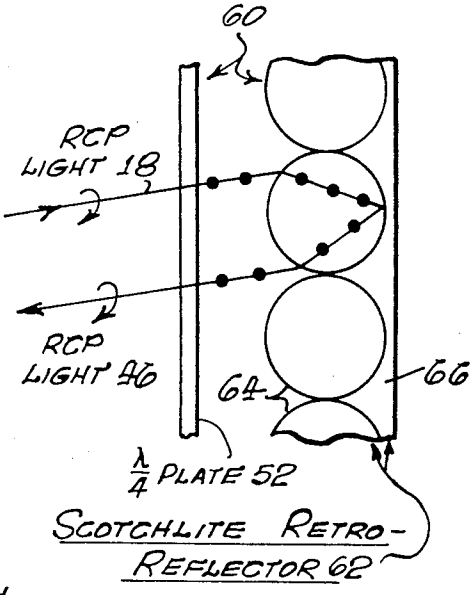


FIG. 2D. TARGET D

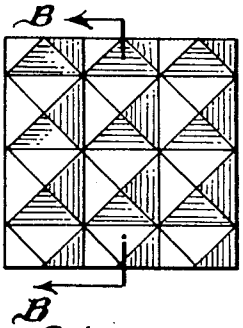
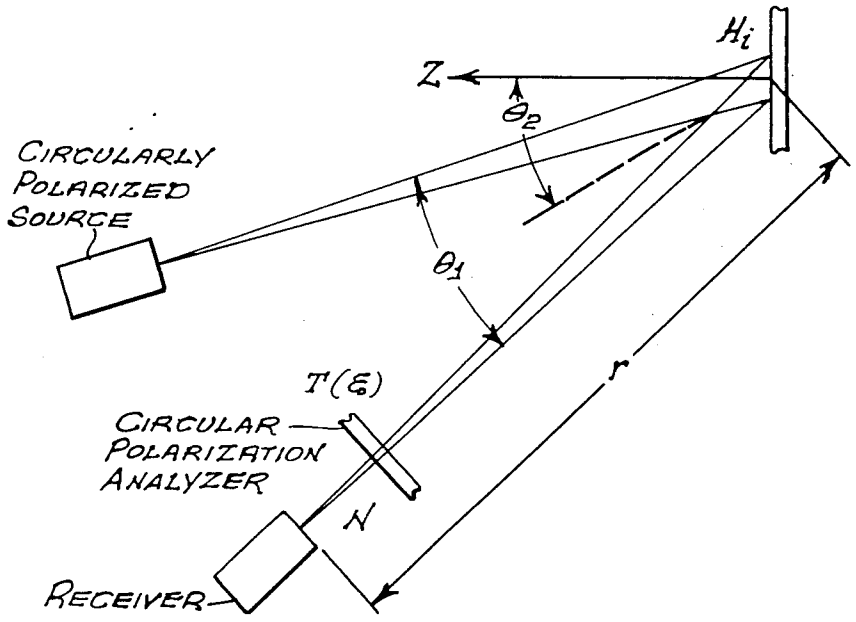


FIG. 2E. FRONT VIEW OF TARGET B.

FIG. 2. POLARIZATION CHARACTERISTICS OF UNDERWATER TARGETS FOR INCIDENT CIRCULARLY POLARIZED LIGHT.



$$N = H_i \; T(\xi) \rho(\theta_1, \theta_2, \phi) \, e^{-\alpha r}$$

N = MEASURED TARGET RADIANCE.

H_i = IRRADIANCE INCIDENT ON THE TARGET.

$T(\xi)$ = TRANSMISSION FACTOR OF THE POLARIZATION ANALYZER.

ξ = DEGREE OF CIRCULAR POLARIZATION OF THE TARGET RADIANCE.

$\rho(\theta_1, \theta_2, \phi)$ = REFLECTION DISTRIBUTION FUNCTION OF THE TARGET.

θ_1 = SOURCE-RECEIVER SEPARATION ANGLE.

θ_2 = POLAR ORIENTATION ANGLE.

ϕ = AZIMUTHAL ORIENTATION ANGLE, WITH RESPECT TO NORMAL TO THE PAGE.

Z = DIRECTION NORMAL TO TARGET.

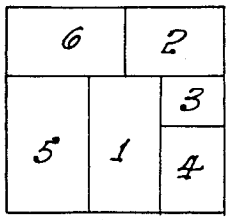
α = VOLUME ATTENUATION COEFFICIENT OF THE MEDIUM.

r = DISTANCE FROM THE TARGET TO THE RECEIVER.

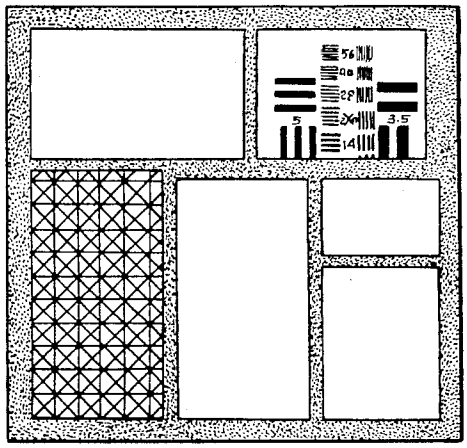
FIG. 3.

EXPERIMENTAL ARRANGEMENT FOR THE MEASUREMENT OF PARAMETERS OF TARGET RADIANCE.

5A.



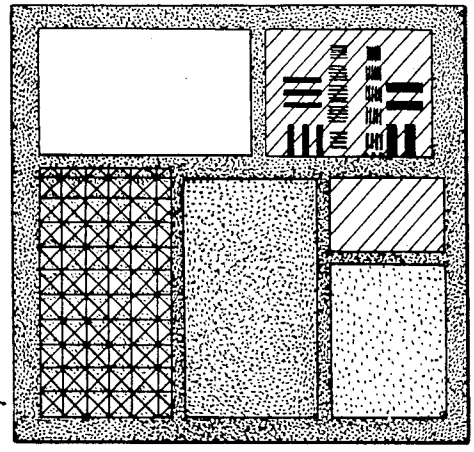
1. DIMPLED REFLECTOR TO SIMULATE BACKSCATTER.
2. DIFFUSE TARGET, TARGET A OF FIG. 2A.
3. SCOTCHLITE RETRO-REFLECTOR.
4. DIMPLED REFLECTOR AND QUARTER-WAVE PLATE, TARGET C OF FIG. 2C.
5. TWO-REFLECTION RETRO-REFLECTOR, TARGET B OF FIG. 2B.
6. SCOTCHLITE AND QUARTER-WAVE PLATE, TARGET D, OF FIG. 2D.



5B.

NO POLARIZATION DISCRIMINATION.

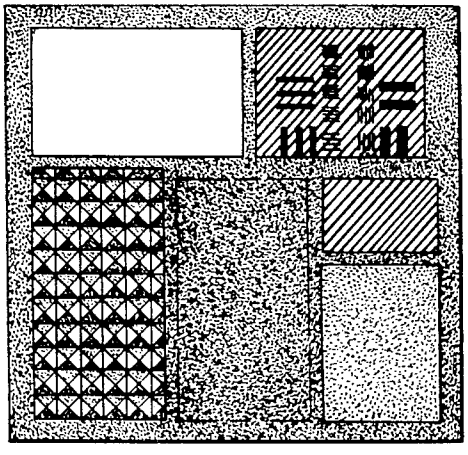
$\theta_2 = 0°$



5C.

CIRCULAR POLARIZATION DISCRIMINATION

$\theta_2 = 0°$



5D.

CIRCULAR POLARIZATION DISCRIMINATION

$\theta_2 = 20°$

FIG. 5.

TARGET RETURNS WITH AND WITHOUT POLARIZATION DISCRIMINATION.

EXTENDED RANGE POLARIZATION TARGET

STATEMENT OF GOVERNMENT INTEREST

The invention described herein may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefor.

BACKGROUND OF THE INVENTION

This invention relates to an apparatus and method for an underwater viewing system wherein much backscattered and sidescattered light is present. When artificial lighting is used underwater, the visibility is often severely limited by light which is scattered from particulate matter and microorganisms in the water back toward the observer or photo-optical receiver. Attempts to reduce the effects of this backscattered light have resulted in investigations into such advanced viewing systems as volume scanning, range gating, and polarization discrimination. Of these advanced systems, polarization discrimination is the easiest to implement.

A polarization discrimination system uses a right circularly polarized (RCP) source of illumination and a right circular analyzer. The backscattered light will in general be left circularly polarized (LCP), and as such will be blocked by the right circular analyzer. The light which returns from most underwater targets will be unpolarized, however, and a portion will be transmitted by the analyzer.

One problem encountered with the polarization discrimination system is the absorption of unpolarized target light. Since it is necessary to eliminate the polarized backscatter, at least half of the unpolarized target light will also be absorbed. With available analyzers the absorption is approximately 63 to 77 percent of the incident value. The output power of the light source could be increased to compensate for this loss, but the additional power drain would be a disadvantage for use on underwater vehicles which have limited energy supplies.

SUMMARY OF THE INVENTION

This invention relates to an apparatus and method for viewing a target area, generally underwater, which permits viewing or otherwise optically detecting the target at ranges which exceed those possible by using presently available targets. The apparatus includes a source of circularly-polarized light for illuminating the target area; a target, at least some portion of which has a retro-reflective surface; a birefringent quarter-wave plate covering the retro-reflective surface of the target; and a circular polarization plate positioned between the viewing lens and the light reflected from the target. The arrangement permits the transmission through the polarization sheet, or polarization plate, of light reflected from the retro-reflective surface which has the same handedness as the light produced by the source.

Since the target will return RCP light rather than unpolarized light, when illuminated with RCP light, approximately twice as much target light will be transmitted by the polarization analyzer. The polarization target will thus appear brighter than conventional targets and can be detected at greater ranges. Since this type of target also redirects a higher percentage of incident light back to the observer, or photo-optical receiver, it will be brighter than conventional targets even when polarization discrimination is not used. Target materials of this type could be bonded to a variety of underwater objects. Since these objects will be visible at greater viewing ranges, they can be located easier than objects not bonded with such materials.

STATEMENT OF THE OBJECTS OF INVENTION

An object of the invention is to provide a reflector material and method for viewing underwater objects which permits more efficient use of the source of light than prior art methods.

Another object of the invention is to provide a reflector material and method suitable for use in an environment where much scattering of reflected light is present.

Still another object is to provide a reflector material which, when bonded or attached to an underwater target, permits locating the target at much greater distances than targets not using this kind of reflector surface.

Other objects, advantages and novel features of the invention will become apparent from the following detailed description of the invention, when considered in conjunction with the accompanying drawings, wherein:

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a diagrammatic view of a prior art circular polarization technique for the elimination of backscatter.

FIG. **2** (A–E) is a set of cross-sectional diagrammatic views showing the polarization characteristics of underwater targets for incident circularly polarized light.

FIG. **3** is a diagrammatic view showing an experimental arrangement for the measurement of parameters of target radiance.

FIG. **4** is a pair of graphs showing the transmission factor of circular polarization analyzers for two different Polaroid materials.

FIG. **5** (A–D) is a set of diagrammatic views showing qualitatively the relative visibility of target returns with and without polarization discrimination.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

One of the problems encountered in underwater viewing is the loss of contrast due to the presence of backscattered light. It has been shown that circular polarization discrimination techniques are effective in some cases as a means of improving target visibility or extending the viewing range.

FIG. **1** illustrates the main components of an extended range or contrast improvement system **10** of the prior art which utilizes circularly polarized light. A source of unpolarized light **12** propagates a beam of unpolarized light **14** through a right circular polarizer **16**, whereupon it becomes right circularly polarized (RCP) light **18**. The RCP light **18**, after impinging upon the target **22**, becomes depolarized target light **24**. There is also a considerable amount of left circularly polarized (LCP) backscattered light **26** produced.

In many cases of underwater viewing, much of the backscattered light 26 is due to single scattering by suspended particles and micro-organisms in the water. If right circularly polarized RCP light 18 is used for illumination, much of the backscattered light 26 is left circularly polarized LCP, and can thus be blocked with a polarization analyzer, right circular analyzer 28. The light 24 returning from most underwater targets 22 is unpolarized, however, and a portion of this target light is transmitted by the analyzer 28, to become polarized light 32 when it enters the detector 34.

The polarization discrimination system 10 shown in FIG. 1 has two fundamental disadvantages. The first is absorption of initially unpolarized source light 14 by the polarizer 16 (approximately 63 percent for Polaroid HNCP37), and the second is absorption of returning target light 24 by the analyzer 28 (another 63 percent).

By using an improved type of polarizer 16, much of the power loss caused by the initial polarization can be eliminated. The second problem, absorption at the analyzer 28, is however, an inherent feature of the polarization discrimination system 10. Since it is necessary to eliminate polarized backscatter 26, at least half of the unpolarized target light 24 will be absorbed.

If targets are designed to return RCP light rather than unpolarized light, approximately twice as much of this target light will be transmitted by a right circular polarization analyzer. If these targets also re-direct a higher percentage of incident light back toward the receiver, they will offer improved contrast and increased viewing ranges even without the use of polarization techniques.

In underwater viewing situations, targets can be classified as uncooperative and cooperative. The former would represent the situation wherein an object is to be found which has not been treated for ease of optical detection e.g., enemy hardware, or the treatment to which the object has been subjected has deteriorated. A cooperative target would be one that is specially treated to effect easy optical detection or recognition.

Referring now to FIG. 2, FIG. 2A shows what happens when RCP light 18 strikes an uncooperative, diffuse, target 22. The reflected light 24 becomes depolarized.

Two different approaches have been taken to design targets which return a large amount of RCP light to the receiver. The first involves the use of a two-reflection retro-reflector 42 which redirects incident light 18 back toward the receiver (not shown) for a variety of target orientations, as shown in FIG. 2B. A retro-reflector may be defined as a reflector wherein the directions of the incident light and the reflected light are approximately parallel. The polarization nature of this target 42 can be explained by resolving the incident RCP light beam 18 into two linearly polarized component beams which have orthogonal electric vectors oscillating at 90° out of phase with each other. For a single reflection from a metal 42 or metallic surface at near-normal incidence, a phase shift of 180° will occur between these two component beams. Since they are originally out of phase by 90°, this additional phase shift produces light which is LCP 44. A second reflection at near-normal incidence introduces another 180° phase shift and the light becomes RCP 46. Although the actual light beam 18 does not strike the metallic surface of the retroreflector 42 at normal incidence, it can be shown that the approximation to 180° phase shifts is reasonably valid except for angles of large incidence. To provide retroreflection characteristics in more than one plane, the actual target 42 is an array of four-corner reflectors. The angles of the target 42 in a plane perpendicular to that shown in FIG. 2B, would generally be at 90° also, as shown in FIG. 2E.

The second approach makes use of birefringent quarter-wave materials and single reflections. One embodiment 50 includes a target which consists of a quarter-wave plate 52 and a dimpled metallic reflector 54, as shown in FIG. 2C. Typical dimpling would consist of indentations one-sixteenth inch deep with a radius of curvature of one-eighth inch, and spaced one-fourth inch apart in a regular hexagonal pattern. The polarization nature of this target 50 can be explained by again resolving the incident RCP light 18 into two linearly polarized components which are 90° out of phase. The two-way path through the quarter-wave plate 52 produces two 90° phase shifts between these components, and one 180° phase shift occurs when the light 18 is reflected at near-normal incidence. Since the total phase shift produced by the target 50 is 360° (or 0°), the returning light 46 will be RCP.

With respect to the type of light source to be used with the reflector material of this invention, it need not be monochromatic, although the quarter-wave plate 52 is more effective with this type of light. For underwater use, a green light source is generally used, and a laser light source would be particularly advantageous. The dimpled surface of the reflector 54 has a semi-diffusing action on the incident light 18 which allows the target 50 to be visible from more than one viewing position. It should be pointed out that the angle θ, between the incident beam 18 and the reflected beam 46,is exaggerated in this figure.

A target 60 which utilizes a quarter-wave plate 52 and a "Scotchlite" reflective sheeting, retro-reflective, material 62 is shown in FIG. 2D. "Scotchlite" reflective sheeting is a trademark of, and manufactured by, the Minnesota Mining and Mfg. Co., Reflective Products Division, St. Paul, Minn. 55119. The "Scotchlite" sheeting 62 is composed of microscopic glass spheres, or beads, 64 of high refractive index which are partially imbedded in a tough plastic reflective substrate 66. The incident light 18 passes through the quarter-wave plate 52, is focused onto the reflecting substrate 66 by the spheres 64, and returns back through the quarter-wave plate in a direction approximately parallel to the incident beam. Although the polarization characteristics are the same as for the previously described model, embodiment 50 of FIG. 2C, this target 60 is much more efficient due to its more complete retro-reflective action.

Referring now to FIG. 3, the measured target radiance is given by

$$N \cong H_i T(\xi) \rho(\theta_1 \theta_2, \phi) e^{-\alpha r} \quad (1)$$

where H_i is the irradiance incident on the target, ρ is the reflection distribution function, α is the volume attenuation coefficient of the medium, and r is the distance from the target to the receiver. If the viewing system employs circular polarization discrimination, the transmission factor of the analyzer is given by $T(\xi)$,

where ξ is the degree of circular polarization for the returning target light. If polarization techniques are not used, $T(\xi)$ is equal to unity.

The degree of circular polarization may be defined operationally as follows: A beam containing a mixture of unpolarized and circularly polarized (CP) light is passed through a birefringent quarter-wave plate and a linear analyzer. The quarter-wave plate converts any CP light to linearly polarized light, but does not affect the unpolarized light. By measuring the degree of linear polarization for this beam we can thus obtain a measure of circular polarization for the original beam. With the preceding arrangement, the degree of circular polarization is given by

$$\xi = \pm[(H_{max} - H_{min})/(H_{max} - H_{min})], \quad (2)$$

where H_{max} and H_{min} are maximum and minimum values for the irradiance which is transmitted by the linear analyzer as it is rotated. This function ranges from zero for unpolarized light to ± 1 for completely circularly polarized light. To differentiate between right and left circularly polarized light, RCP values are considered to be positive and LCP values negative.

By measuring ξ in this manner, it is not necessary to assume a particular functional relationship between ξ and $T(\xi)$, the transmission of a circular analyzer. Once such transmission curves are known, however, the degree of circular polarization is easily determined by measuring $T(\xi)$.

Referring now to FIG. 3, equation 1 indicates that the measured target radiance can be increased by increasing $\rho(\theta_1, \theta_2, \phi)$ for values of θ_1, θ_2 and ϕ, which are commonly used with underwater viewing systems. If circular polarization techniques are being used, then $T(\xi)$ should also be as high as possible.

The transmission characteristics of Polaroid HNCP37 and HGCP21 analyzers were measured as a function of degree of circular polarization for the incident light. These curves, shown in FIG. 4, indicate that $T(\xi)$, and thus the measured target radiance, is a linear function of the degree of circular polarization. The empirical equations which represent these curves are:

$$T(\xi) = 0.36\,\xi + 0.37 \quad \text{(HNCP37)}, \quad (3)$$

and

$$T(\xi) = 0.23\,\xi + 0.23 \quad \text{(HGCP21)}. \quad (4)$$

From Eqs. 3 and 4, we have

$$\xi = [T(\xi)/T(\xi = 0)] - 1. \quad (5)$$

It may be shown that ξ, as determined by this method, is identical to the fourth normalized Stokes parameter.

Qualitative and quantitative investigations were performed to compare the efficiencies of several underwater targets.

Qualitative representations of photographs of various targets are shown in FIG. 5. The source-receiver separation angle θ_1 was fixed at approximately 10° (see FIG. 3), and identical exposure times and aperture settings were used for all three photographs. Circular polarization discrimination was effected by placing a Polaroid HGCP21 circular analyzer in front of the camera lens. From this figure several qualitative observations can be made. When circular polarization discrimination is used:

1. RCP light which undergoes a single reflection is effectively blocked by the analyzer. A single reflection at near-normal incidence produces a 180° phase shift between orthogonally polarized components, and thus converts RCP light to LCP light. See FIG. 2B.
2. The brightness of a typical white diffuse target, target 2, is considerably reduced.
3. Ordinary Scotchlite, target 3, is no brighter than the white diffuse target, target 2.
4. The brightness of a dimpled reflector, target 1, is considerably improved by covering it with a quarter-wave birefringent plate, target 4. For $\theta_2 > 0$, however, this combination is not as bright as the white diffuse target, target 2. Refer to FIG. 3 for a definition of θ_2, the polar orientation angle.
5. Return from the two-reflection retro-reflector, target 5, is excellent for $\theta_2 = 0$, but rapidly decreases as θ_2 increases.
6. The Scotchlite and quarter-wave plate combination, target 6, is considerably brighter than the white diffuse target, target 2. This brightness does not significantly decrease as θ_2 increases.

To determine the contrast improvement or range increase obtained by using improved targets, it was necessary to measure quantitatively the target radiances as a function of the source-receiver separation angle θ_1, and the polar orientation angle θ_2. See FIG. 3. Specification of an azimuthal orientation angle ϕ is only necessary for the two reflection retro-reflector shown in FIG. 2E, since the other targets possess azimuthal symmetry. For this target, ϕ is arbitrarily set equal to zero when two sides of the rectangular retro-reflector array (FIG. 5) are parallel (or perpendicular) to the plane of incidence.

Measurements were taken for four targets which, for simplicity, are designated by the letters A, B, C, and D as follows, in accordance with the designations shown in FIG. 2:

A — white diffuse target,
B — two reflection retro-reflector,
C — dimpled reflector and quarter-wave plate,
D — Scotchlite sheeting and quarter-wave plate.

The range of each of these targets was fixed at approximately 4.2 meters, and relative radiance was measured with a Gamma Scientific model 2,000 telephotometer. The illuminating source was circularly polarized by use of HGCP21 Polaroid, and polarization discrimination was effected by placing an HNCP37 Polaroid analyzer over the telephotometer lens.

The relative radiance of these targets was measured both with and without polarization discrimination for values of θ_2 between 0° and 50°, and values of θ_1 between 1.74° and 10°. For a linear source-receiver separation distance of 20 inches, this range of values for θ_1 corresponds to a range of viewing distances between 16.7 meters ($\theta_1 = 1.74°$) and 2.9 meters ($\theta_1 = 10°$).

It was determined that targets D, Scotchlite and quarter-wave plate; B, two reflection retro-reflector; and C, dimpled reflector and quarter-wave plate; were all brighter than target A, white diffuse target, for small polar orientation angles. It was also determined that for a given target orientation, that is, for fixed values of θ_1, θ_2 and θ, the improvement is generally greater with polarization discrimination than it is without it.

For many orientation and separation angles, however, two of these targets, B and C, are less bright than target A. When polarization discrimination is not used, target C is brighter than target A only for values of θ_2 which range from zero to approximately 10°. When polarization discrimination is used, this range increases to approximately 15°. When $\theta = 0$, target B is brighter than target A for values of θ_2 up to approximately 25°. When polarization discrimination is not being used, there is also a large increase in radiance for $\theta_2 \cong 45°$.

From FIG. 2B it can be seen that when $\theta_2 = 45°$, the bisector of θ_1 will be normal to one set of reflecting facets on the target, and light will return to the receiver after being singly reflected. Since RCP light becomes LCP when it is singly reflected at near-normal incidence, much lower radiance values are obtained for $\theta_2 \cong 45°$ when polarization discrimination is employed. If ϕ is not equal to zero (or multiples of 90°), the measured radiance of target B is greatly reduced since twice-reflected light does not return to the receiver. It can also be shown that with $\phi = 45°$, the measured radiance of this target very rapidly drops below that of target A as θ_2 is increased.

The most significant improvement was obtained with target D, Scotchlite and quarter-wave plate. This target was brighter than any of the others for a wide variety of target orientations. Due to its retro-reflecting characteristics, the improvement is most pronounced for small source-receiver separation angles (long ranges), and decreases as this angle increases.

Measurement of the effect of polarization discrimination on the measured radiance of targets A and D show that approximately 71 percent of the light returning from target D is transmitted by an HNCP37 analyzer. For target A, approximately 37 percent of the returning light passes through the analyzer.

By referring to the $T(\xi)$ versus ξ curve for HNCP37 Polaroid shown in FIG. 4, it can be seen that the light returning from target D is almost completely RCP, and that returning from target A is unpolarized. These polarization characteristics are largely independent of the source-receiver separation and the polar orientation angle.

In summary, quantitative radiance measurements have been made for three newly developed targets, targets B, C, and D of FIG. 2, and for one white diffuse comparison target, target A. These measurements indicate that significant range increases are possible when one of these targets, target D, Scotchlite and quarter-wave plate, is used with either a conventional viewing system or with one which employs polarization techniques to discriminate against backscatter.

For source-receiver separation angles between 1.74° and 10°, the radiance of this target D was between 1.79 and 33.2 times that of the comparison target, target A. The calculated range increases afforded by using this target are between 0.5 and 1.5 attenuation lengths. The specific radiance improvement factor, and associated range increase, for a particular viewing system depends on whether or not polarization discrimination is employed and on the source-receiver separation angles involved. In general, greater radiance improvements are obtained when polarization techniques are employed, and when source-receiver separation angles are small.

If a target is constructed from Scotchlite and very thin, flexible quarter-wave material, it could be bonded to a variety of underwater objects, such as, test torpedoes, diver marking aids, tools, diver's suits, underwater habitats, etc. These objects would then be visible at greater viewing ranges, and could be more easily located.

Obviously many modifications and variations of the present invention are possible in the light of the above teachings. It is therefore to be understood that within the scope of the appended claims the invention may be practiced otherwise than as specifically described.

What is claimed is:

1. a reflector, particularly useful for underwater use, comprising:
   - a base material;
   - the base material having a single-reflection retro-reflective, dimpled, surface, the dimples being in the range of 1.5mm deep, with a radius of curvature of approximately 3.0mm, and spaced approximately 6mm apart; and
   - a sheet of birefringent quarter-wave plate disposed upon the dimpled surface.

2. A reflector particularly useful for underwater use, comprising:
   - a plastic substrate;
   - a plurality of transparent glass, microscopic, spheres imbedded in the substrate;
   - the surfaces of intersection of the spheres and the substrate forming a reflective surface; and
   - a sheet of birefringent quarter-wave plate disposed upon, or adjacent to, the imbedded spheres, parallel to the substrate.

* * * * *