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(72) Inventeurs/Inventors:
KATHMAN, ALAN D., US;
JOHNSON, ERIC G., US;
FEDOR, ADAM S., US;
MORRIS, JAMES E., JR., US

(73) Propriétaire/Owner:
DIGITAL OPTICS CORPORATION, US

(74) Agent: BORDEN LADNER GERVAIS LLP

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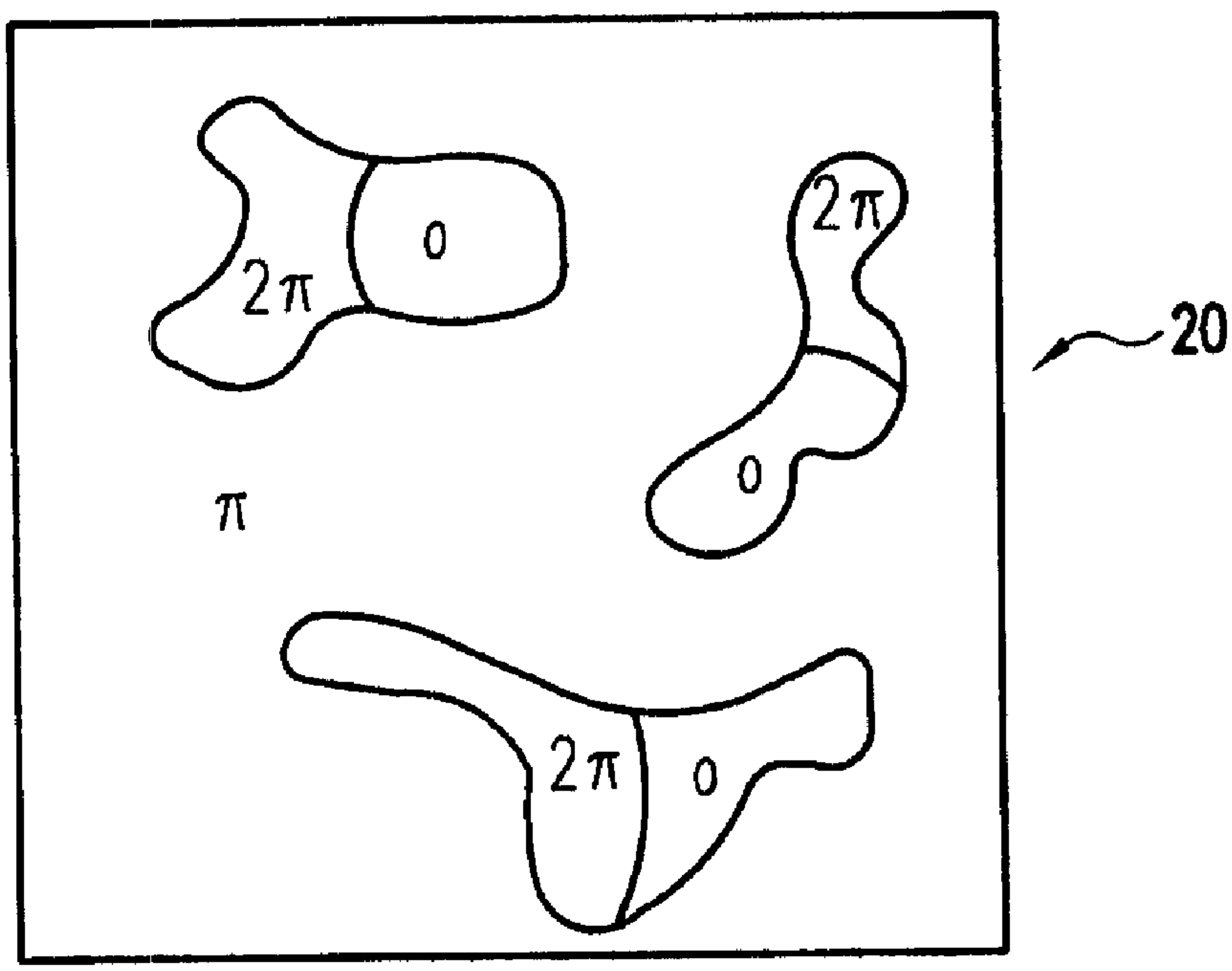

(57) Abrégé/Abstract:
A broadband diffractive diffuser contains at least three levels, with approximately a phase shift of π between at least two of the at least three levels. Such a diffuser provides light with more than two phasor vectors at the zero order. The presence of the more than two phasor vectors reduces the zero order diffraction efficiency at non-design wavelength, increasing the usefulness of the diffuser at wavelengths other than the design wavelength. Preferably, the diffractive diffuser includes a plurality of regions, approximately 50 % of an area of the plurality of regions presenting a phase shift of π at a design wavelength, approximately 25 % of the area of the plurality of regions presenting a phase shift of 2π at the design wavelength, and approximately 25 % of the area of the plurality of regions presenting a phase shift of 0 at the design wavelength. Such a diffractive diffuser may be formed by logical operations between two diffractive diffuser patterns, by adding two diffractive diffuser patterns, or by pixel-by-pixel scanning.

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(71) Applicant (*for all designated States except US*): DIGITAL OPTICS CORPORATION [US/US]; Suite J, 5900 Northwoods Parkway, Charlotte, NC 28269 (US).

(72) Inventors; and
(75) Inventors/Applicants (*for US only*): KATHMAN, Alan, D. [US/US]; 4700 Lone Tree Lane, Charlotte, NC 28269 (US). JOHNSON, Eric, G. [US/US]; 5721 Whitegate Lane, Charlotte, NC 28269 (US). FEDOR, Adam, S. [US/US]; 2735 Bishopton Place, Charlotte, NC 28216 (US). MORRIS, James, E., Jr. [US/US]; Leipzig Drive, Charlotte, NC 28210 (US).

(74) Agent: MORSE, Susan, S.; Jones Volentine, L.L.P., Suite 150, 12200 Sunrise Valley Drive, Reston, VA 20191 (US).

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(54) Title: BROADBAND DIFFRACTIVE DIFFUSER AND ASSOCIATED METHODS

(57) Abstract

A broadband diffractive diffuser contains at least three levels, with approximately a phase shift of π between at least two of the at least three levels. Such a diffuser provides light with more than two phasor vectors at the zero order. The presence of the more than two phasor vectors reduces the zero order diffraction efficiency at non–design wavelength, increasing the usefulness of the diffuser at wavelengths other than the design wavelength. Preferably, the diffractive diffuser includes a plurality of regions, approximately 50 % of an area of the plurality of regions presenting a phase shift of π at a design wavelength, approximately 25 % of the area of the plurality of regions presenting a phase shift of 2π at the design wavelength, and approximately 25 % of the area of the plurality of regions presenting a phase shift of 0 at the design wavelength. Such a diffractive diffuser may be formed by logical operations between two diffractive diffuser patterns, by adding two diffractive diffuser patterns, or by pixel–by–pixel scanning.

BROADBAND DIFFRACTIVE DIFFUSER AND ASSOCIATED METHODS

Field of the Invention

The present invention is directed to diffractive diffusers, in particular to broadband diffractive diffusers.

Description of Related Art

A binary or diffractive diffuser functions well as its design wavelength, but suffers significant contributions from the zero-order as the wavelength deviates from the design wavelength. The zero-order contributions arise from that light which is not diffracted. This will lead to undesirable peaks in intensity when the design wavelength is deviated from.

A schematic view of a prior art binary diffuser is shown in Figure 1. In Figure 1, a binary or diffractive diffuser 10 consists of amorphous, free-form regions roughly evenly split between regions presenting a zero phase shift and regions presenting a π phase shift to incoming light. These regions are so labeled in Figure 1. These regions are formed the different etching depths shown in the prior art of Figure 2. The zero regions are not etched at all, while the π regions are etched to a depth of d_1, where $d_1=\lambda_0/2(n-1)$, where λ_0 is the design wavelength and n is the index of refraction of the diffuser. Thus, at the design wavelength, the etched portions present a phase shift of π or $\lambda_0/2$ to the incoming light.

Light at different wavelengths will interact with the diffuser 10 as shown in the phasor histograms in prior art Figures 3a-3c. When an input wavelength λ is the design wavelength λ_0, the zero order contributions from the zero regions and the π regions cancel each other, thereby resulting in no zero order contribution, as shown in Figure 3a. When the input wavelength λ is less than the design wavelength, as shown in Figure 3b, for the phase shift of zero, the zero order contribution will be the same as that for the design wavelength, i.e., zero. However, for the portions etched to the depth of d_1, this depth will no longer look like a phase shift of π to the input wavelength, but rather a phase shift of greater than π. The resultant vector 12 has an amplitude of $\sin^2[(\pi/2)\, \lambda_0/ \lambda -1)]$. Similarly, when the input wavelength λ is greater than the design wavelength, as shown in Figure 3c, the portions etched to the depth of d_1 will present a phase shift of less than π, with a resultant vector 14 having an amplitude of $\sin^2 ((\pi/2)\, (\lambda_0/ \lambda -1))$.

The shift of the phasor vector for the π phase shift regions away from the axis so as to cancel the contribution from the zero phase shift regions reduces the efficiency of the diffuser 10 at wavelengths other than the design wavelength. For example, in the range of $\lambda = .83\ \lambda_0$ to $\lambda = 1.20\ \lambda_0$, the zero order diffraction efficiency will be as high as 10%, i.e., 10% of the input beam will be delivered to the zero order, severely reducing the efficiency and general usefulness of the diffuser 10.

Summary of the Present Invention

Therefore, it is an object of the present invention to provide a diffractive diffuser that is less sensitive to deviations from a design wavelength, i.e., a broadband diffractive diffuser.

It is further an object of the present invention to provide a diffractive diffuser having at least three discrete levels. At least tow of the levels may have a phase difference of approximately π between them.

It is further an object of the present invention to provide a broadband diffractive diffuser including a computer generated hologram designed at a wavelength λ_0 for which light of a wavelength λ incident thereon has a total power in a zeroth order of less than $\sin^2((\pi/2)(\lambda_0/\lambda-1))$. Such a diffuser may, for $0.83\lambda_0 \leq \lambda$ \$ $1.20\lambda_0$, have a zeroth order be $\sin^4((\pi/2)(\lambda_0/\lambda-1))$.

It is an additional object of the present invention to provide a broadband diffractive diffuser including a computer generated hologram designed at a wavelength λ_0 for which light of a wavelength λ, $0.83\lambda_0 \leq \lambda$ \$ $1.20\lambda_0$, incident thereon has a zero order diffraction efficiency of less than 1%.

It is another object of the present invention to provide a diffractive diffuser including a plurality of regions, approximately 50% of an area of the plurality of regions presenting a phase shift of π at a design wavelength, approximately 25% of the area of the plurality of regions presenting a phase shift of 2π at the design wavelength, and approximately 25% of the area of the plurality of regions presenting a phase shift of 0.

It is further an object of the present invention to provide a diffractive diffuser having a plurality of regions designed to operate at a design wavelength, while the diffractive diffuser provides light at a wavelength other than the design wavelength with more than two phasor vectors at zero order.

It is further an object of the present invention to provide a method of designing a broadband diffractive diffuser. The method includes generating a diffractive diffuser pattern at a design wavelength and modifying the diffractive diffuser pattern to provide light at a wavelength other than the design wavelength with more than two phasor vectors at zero order.

The modifying may include generating a different diffractive diffuser pattern at the design wavelength and performing a logical operation between regions of the diffractive diffuser pattern which present a zero phase shift with the different diffractive diffuser pattern. The generating of the different diffractive diffuser pattern may include rotating the diffractive diffuser pattern. The logical operation may be an AND operation.

Alternatively, the modifying may include generating a different diffractive diffuser pattern and adding phases of said different diffuser pattern to corresponding phases of the diffractive diffuser patter. This adding may include the diffractive diffuser pattern forming an undersized desired output, the different diffractive diffuser pattern forming a spot, and a modified pattern formed by adding phases of the different diffractive diffuser pattern and the diffractive diffuser pattern generating a desired output.

Alternatively, the generating may include splitting the diffuser into regions having a phase shift of π and regions having a phase shift of zero at the design wavelength, and the modifying may include splitting regions having a phase shift of zero into regions having a phase shift of zero and regions having a phase shift of 2π at the design wavelength. At least one of the splittings may be even. At least one of the splittings may result in amorphous regions. The splittings may include a pixel-by-pixel search.

In accordance with the above objects, the plurality of regions may have an amorphous shape. The plurality of regions may be formed by a computer-generated hologram.

Further scope of applicability of the present invention will become apparent from the detailed description given hereinafter. However, it should be understood that the detailed description and specific examples, while indicating preferred embodiments of the invention, are given by way of illustration only, since various changes and modifications within the spirit and scope of the invention will become apparent to those skilled in the art from this detailed description.

Brief Description of the Drawings

The present invention will become more fully understood from the detailed description given hereinbelow and the accompanying drawings which are given by way of illustration only, and thus are not limitative of the present invention, and wherein:

Figure 1 is a schematic illustration of a related diffractive diffuser;

Figure 2 illustrates the etch depth for the diffractive diffuser shown in Figure 1;

Figure 3a is a phasor histogram of the zero order contribution for the diffractive diffuser shown in Figure 1 at the design wavelength;

Figure 3b is a phasor histogram of the zero order contribution for the diffractive diffuser shown in Figure 1 for wavelengths less than the design wavelengths;

Figure 3c is a phasor histogram of the zero order contribution for the diffractive diffuser shown in Figure 1 for wavelengths greater than the design wavelengths;

Figure 4 is a schematic diagram of a broadband diffractive diffuse element in accordance with the present invention;

Figure 5 illustrates the etch depths for the diffractive diffuse of Figure 4;

Figure 6a is a phasor histogram of the zero order contribution for the diffractive diffuser shown in Figure 4 at the design wavelength;

Figure 6b is a phasor histogram of the zero order contribution for the diffractive diffuser when the input wavelength is less than the design wavelength; and

Figure 6c is a phasor histogram of the zero order contribution for the diffractive diffuser shown in Figure 4 when the wavelength is greater than the design wavelength.

Detailed Description of the Preferred Embodiments

Figure 4 is a schematic diagram of a diffractive diffuser 20 in accordance with the present invention. As can be seen therein, the zero regions have been subdivided into subsets of zero and 2π. While in Figure 4, the previously zero regions have been roughly divided in half to split between the zero and 2π regions, these regions may be subdivided in many ways as long as over entire surface approximately 50% of the surface presents a phase shift of π to the design wavelength, approximately 25% of the surface presents a phase shift of zero to the design wavelength, and the remaining 25% of the surface presents a phase shift of 2π to the design wavelength.

The etch depths for the diffractive diffuser 20 are shown in Figure 5. Again, $d_1=\lambda_0/2(n-1)$ while the additional depth $d_2=\lambda_0/(n-1)$. Thus, the design wavelength, the depth d_2 presents a phase shift of 2π and the depth d1 presents a phase shift of π. At the design wavelength, a phase shift of zero and a phase shift of 2π are mathematically identical. Thus, the diffractive diffuser 20 will function identically to the diffractive diffuser 10 at the design wavelength. However, the inclusion of the phase shift 2π at the design wavelength will result in a third vector of the zero order contribution for wavelengths other than the design wavelength. This third vector, when summed with the other vectors arising from the phase shift of zero and the phase shift of π, will reduce the amplitude of the resultant vector. This is shown in Figures 6a through Figures 6c.

As can be seen in Figure 6a, the zero order contribution when the input wavelength is the design wavelength is still zero, since the phase shift of zero and 2π will look the same at the design wavelength. As shown in Figure 6b, when the input wavelength is less than the design wavelength, there will be a third phasor vector arising from the presence of the 2π portions. The resultant vector 22 will have an amplitude of $\sin^4((\pi/2)(\lambda_0/\lambda-1))$. Thus, the zero order contribution will be significantly reduced from that previously shown in Figure 3b. Similarly, in Figure 6c, the resultant vector 24 will have an amplitude of $\sin^4((\pi/2)(\lambda_0/\lambda - 1))$. For the range noted previously of $\lambda = .83\ \lambda_0$ through $\lambda = 1.20\ \lambda_0$, the zero order diffraction deficiency is reduced to less than 1%. Thus, the magnitude of the zero order contribution of the diffuser 20 for the non-design wavelengths is reduced by an order of magnitude compared with the diffuser 10.

The diffuser 20 of the present invention may advantageously be produced by generating two patterns for a diffuser as shown in Figure 1 and then logically combining these patterns. More specifically, a first diffractive diffuser pattern is generated and a second diffractive diffuser pattern is generated and superimposed on the first pattern. The zero regions of the first generated pattern may then be subjected to, for example, an AND operation with the second generated pattern to form the regions of zero and 2π. For example, when ANDing the two patterns, when both regions are zero, that region will remain a zero region, when both regions are π regions, that region will remain a π region, but if the region is zero in one pattern and π in the other pattern, that region will become a 2π region. Of course logical operations may be performed mathematically using functions describing the respective patterns.

As an example, a single pattern as shown in Figure 1 is generated, and then this pattern is rotated by 90E and used as the second generated pattern. The single pattern is generated in accordance with a desired distribution over a desired region of a desired shape at the design wavelength. These two patterns are then ANDed to form the pattern having the three phase regions distributed thereon.

Another method using two patterns involves adding the phases in corresponding regions in two binary patterns. In this method, where both patterns are 0, the final pattern has a phase of 0, when both are π, the final pattern has a phase of 2π, and where one pattern is 0 and one is π, the final pattern has a phase of π. The final or resulting pattern in the input plane is the Fourier Transform pattern of the desired output. The addition of the phases in the input plane, which is the spatial domain, results in the convolution of the pattern in the output plane, which is the frequency domain. Thus, when adding the phases within two patterns, these patterns are designed to account for the fact that their respective outputs will be convolved.

For example, a first pattern may be generated in accordance with the desired output at the design wavelength, but having an output that is slightly smaller than the desired output. The second pattern is then generated to form a small spot in the output plane. When the phases of this second pattern are added to the phases of the first pattern, the resulting pattern has 0, π and 2π regions, and the resulting output is larger than the output of the first pattern, thereby forming the desired output. Thus, the first and second patterns are designed in relation to one another so that the second pattern increases the size, or blurs, the first pattern to form the desired output. In this example, the first pattern contains the high frequency information needed to generate the desired output, while the second pattern contains the low frequency information needed to generate the desired output.

An alternative manner of zero-order balancing the broadband diffuser 20 involves a fractal method of splitting the zero regions into regions of zero and 2π. A single diffuser pattern is generated, then searched to determine regions where the phase is zero. This search involves scanning every pixel in the pattern until a pixel with zero phase is encountered. Then every pixel in this zero phase region is traversed, e.g., in a four connected fashion, e.g., examining the top, bottom, left and right pixels adjacent to the current pixel. This traversal proceeds until every zero phase pixel that is contiguously connected to the region is encountered. Each such zero phase pixel is flagged with an identifier indicating that it is part of the connected region. The connected region is then traversed again from both sides, preferably starting with the first pixel and the last pixel encountered in the connected region. Pixels on either side are flagged with different identifiers until the region is divided approximately in half. One-half of the region is then set to have a phase of 2π and the other half is left having the zero phase. This process is repeated for each zero phase region in the original diffuser pattern.

The initial diffuser patterns are formed as set forth in U.S. Patent No. 5,850,300 issued 15 December 1998, in which a diffuser is to have a desired line width and the line widths are oriented randomly. These line widths determine the angular region of the diffused beam in the far field. The resulting computer generated pattern or hologram is a Fourier Transform pattern that corresponds to the desired angular region. The preferred method of generating such a pattern is using an iterative computer optimization technique, such as the IDO method described in <u>Iterative Encoding of</u>

High Efficiency Holograms for Generation of Spot Arrays, Optics Letters, Vol. 14, pp. 479-81, 1989. The resulting hologram may be constructed in known manners, such as set forth in U.S. Patent Nos. 4,895,790 and 5,202,775.

The three different methods set forth above for forming the diffractive diffuser in accordance with the present invention may result in a different final pattern for the broadband diffuser, but all the final patterns should have three levels and a phase difference approximately equal to π between at least two of the levels. Advantageously for the final patterns, approximately 50% of the surface presents a phase shift of π to the design wavelength, approximately 25% of the surface presents a phase shift of zero to the design wavelength, and the remaining 25% of the surface presents a phase shift of 2π to the design wavelength.

The invention being thus described, it will be obvious that the same may be varied in many ways. For example, the π regions may similarly be split into π regions and 3π regions, to reduce the resultant vector for non-design wavelengths. Such variations are not to be regarded as a departure from the spirit and scope of the invention, and all such modifications as would be obvious to one skilled in the art are intended to be included within the scope of the following claims.

1. A diffractive diffuser comprising a plurality of regions of an amorphous shape, approximately 50% of an area of said plurality of regions presenting a phase shift of π at a design wavelength, approximately 25% of the area of said plurality of regions presenting a phase shift of 2π at the design wavelength, and approximately 25% of the area of said plurality of regions presenting a phase shift of 0.

2. The diffractive diffuser according to claim 1, wherein said plurality of regions is formed by a computer generated hologram.

3. A method of designing a broadband diffractive diffuser comprising:

generating a first diffractive diffuser pattern at a design wavelength; and

modifying the first diffractive diffuser pattern to provide light at a wavelength other than the design wavelength with more phasor vectors at zero order than light at the design wavelength by generating a second diffractive diffuser pattern and adding phases of said second diffuser pattern to corresponding phases of said first diffractive diffuser pattern wherein said first diffractive diffuser pattern forms an undersized desired output, said second diffractive diffuser pattern forms a spot and wherein a modified pattern formed by the addition of the phases of said second diffractive diffuser pattern and said first diffractive diffuser pattern generates a desired output.

4. A method of designing a broadband diffractive diffuser comprising:

generating a first diffractive diffuser pattern at a design wavelength; and

modifying the first diffractive diffuser pattern to provide light at a wavelength other than the design wavelength with more phasor vectors at zero order than light at the design wavelength by generating a second diffractive diffuser pattern at the design wavelength, said second diffractive diffuser pattern being different than said first diffractive diffuser pattern, and adding regions of said first diffractive diffuser pattern which present a zero phase shift and said second different diffractive diffuser pattern wherein said first diffractive diffuser pattern forms an undersized desired output, said second diffractive diffuser pattern forms a spot and wherein a modified pattern formed by the addition of the phases of said second diffractive diffuser pattern and said first diffractive diffuser pattern generates a desired output.

5. The method according to claim 4, wherein said generating said second diffractive diffuser pattern includes rotating said first diffractive diffuser pattern.

6. A method of designing a broadband diffractive diffuser comprising:

generating a first diffractive diffuser pattern at a design wavelength by splitting the diffuser into regions having a phase shift of π and regions having a phase shift of zero at the design wavelength; and

modifying the first diffractive diffuser pattern to provide light at a wavelength other than the design wavelength with more phasor vectors at zero order than light at the design wavelength by splitting regions having a phase shift of zero into regions having a phase shift of zero and regions having a phase shift of 2π at the design wavelength.

7. The method according to claim 6, wherein at least one of said splittings is even.

8. The method according to claim 6, wherein at least one of said splittings results in amorphous regions.

9. The method according to claim 6, wherein said splittings include a pixel-by-pixel search.

10. The method according to claim 3, wherein said generating and modifying are performed on a computer to form a computer generated hologram.

11. The method according to claim 3, further comprising photolithographically creating a modified diffractive diffuser pattern output by said modifying.

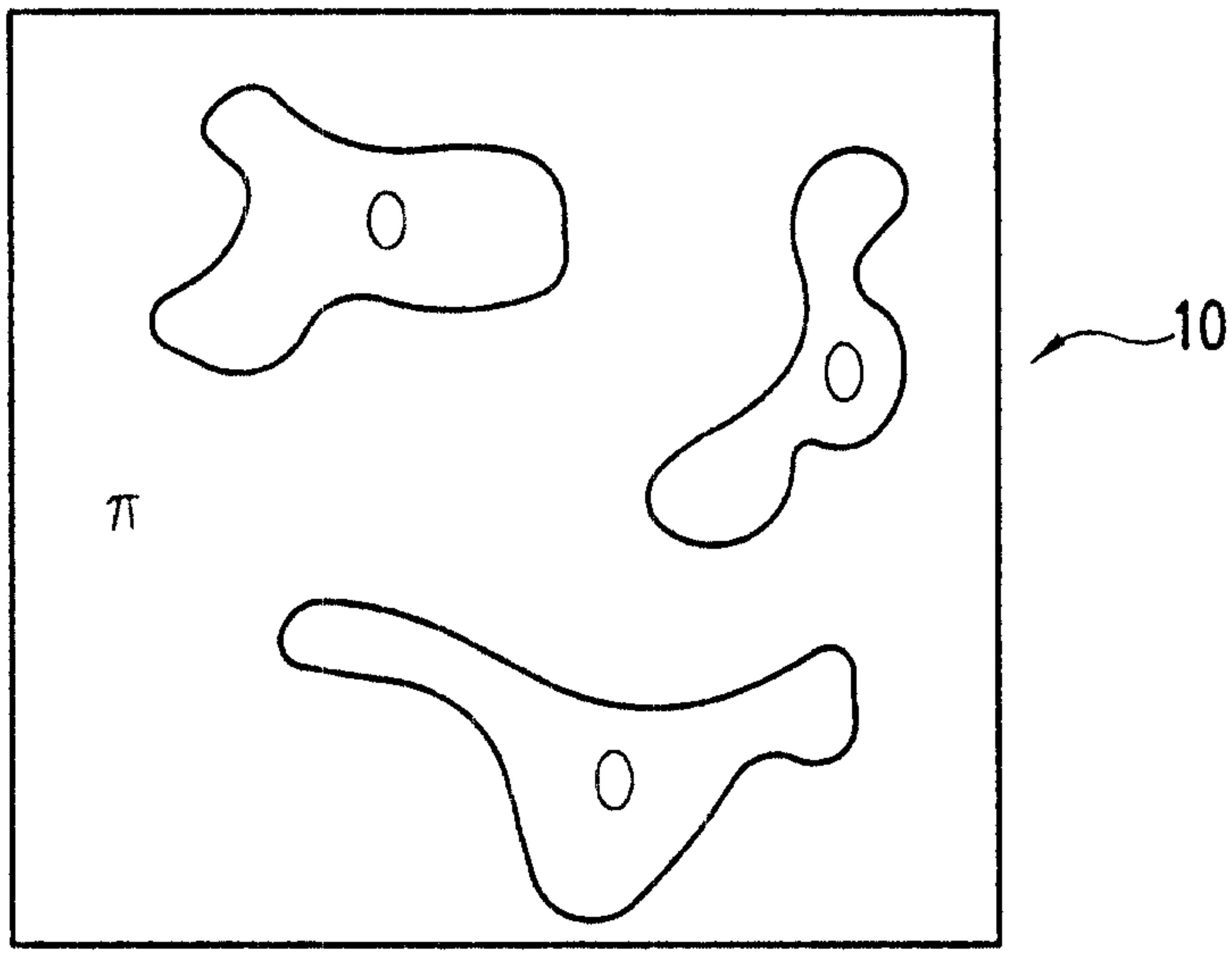


FIG.1

(PRIOR ART)

FIG.2

(PRIOR ART)

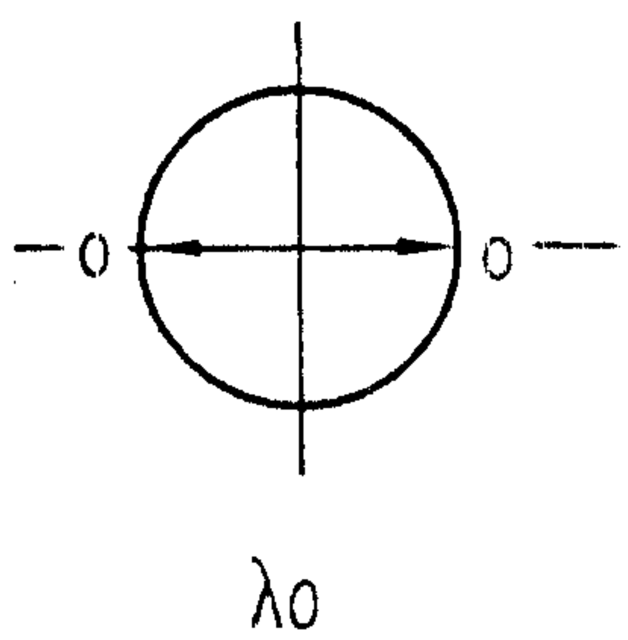


FIG.3A

(PRIOR ART)

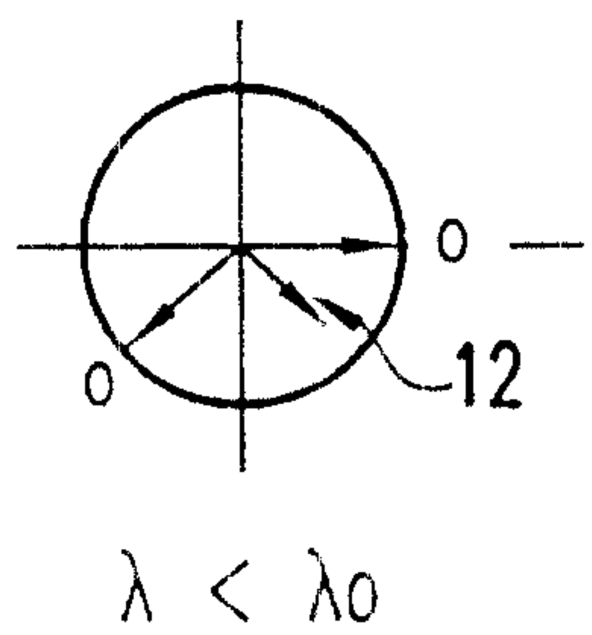


FIG.3B

(PRIOR ART)

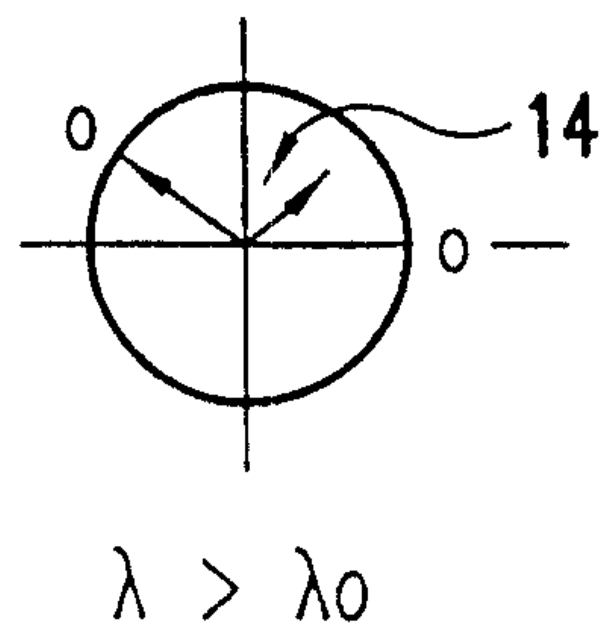


FIG.3C

(PRIOR ART)

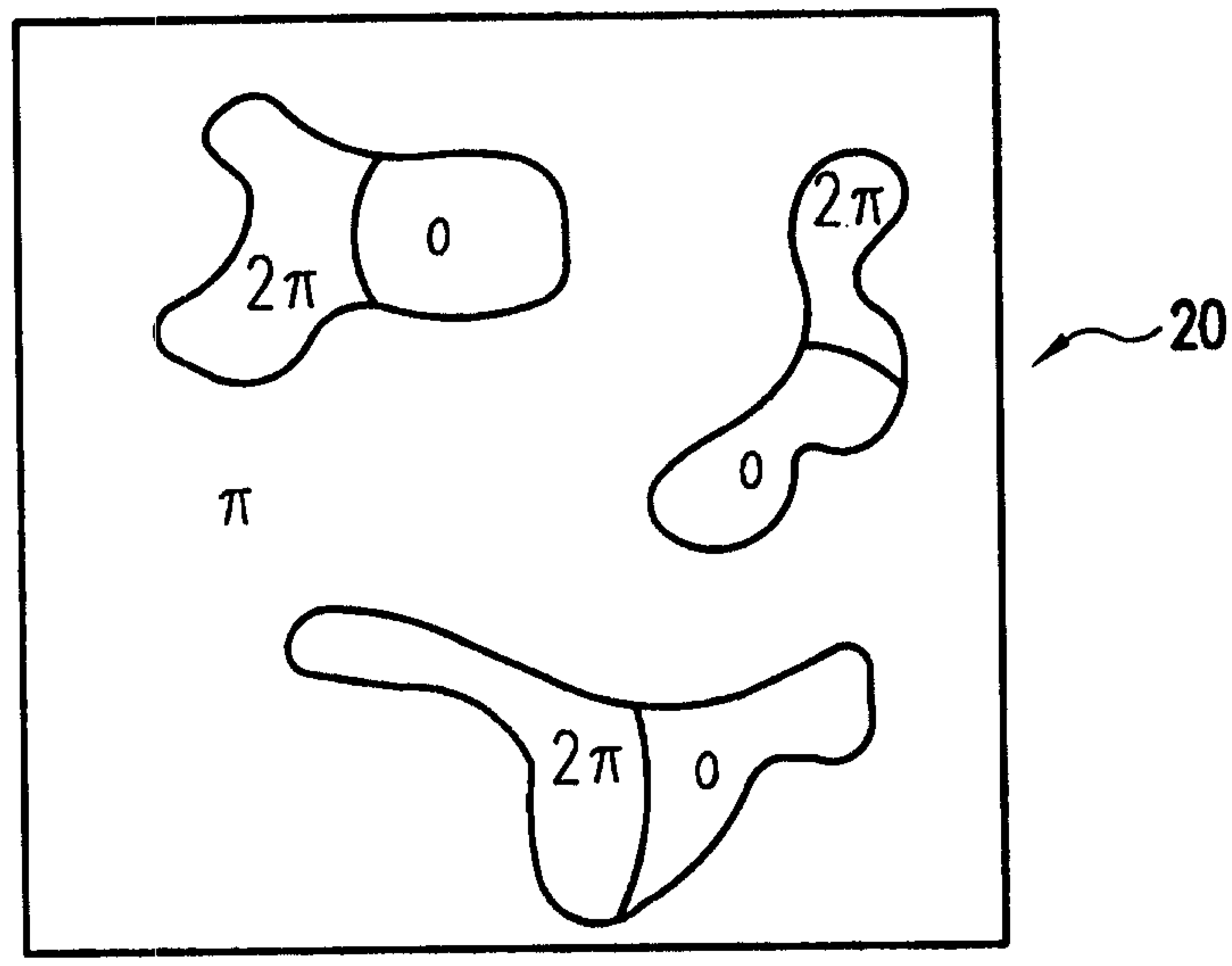
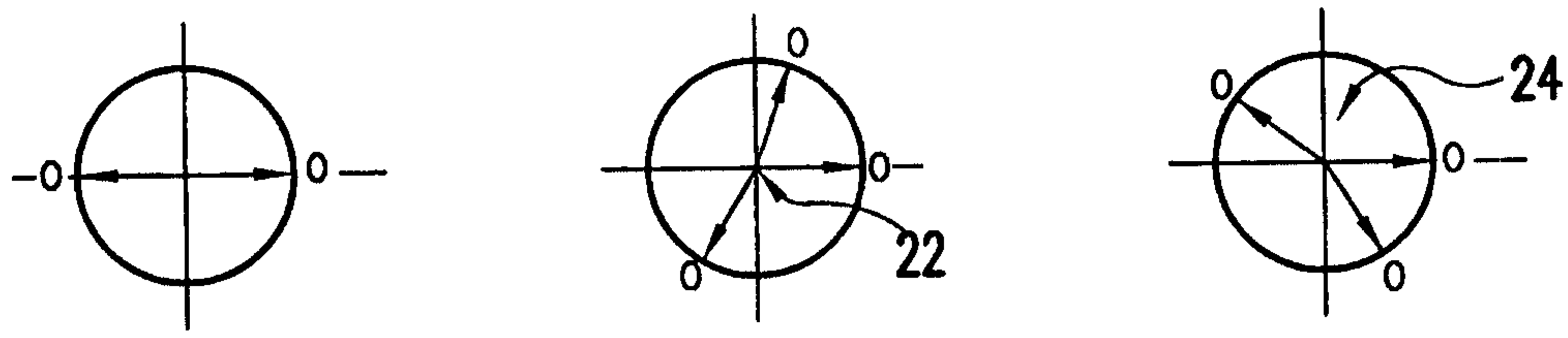


FIG.4

FIG.5



λ = λo

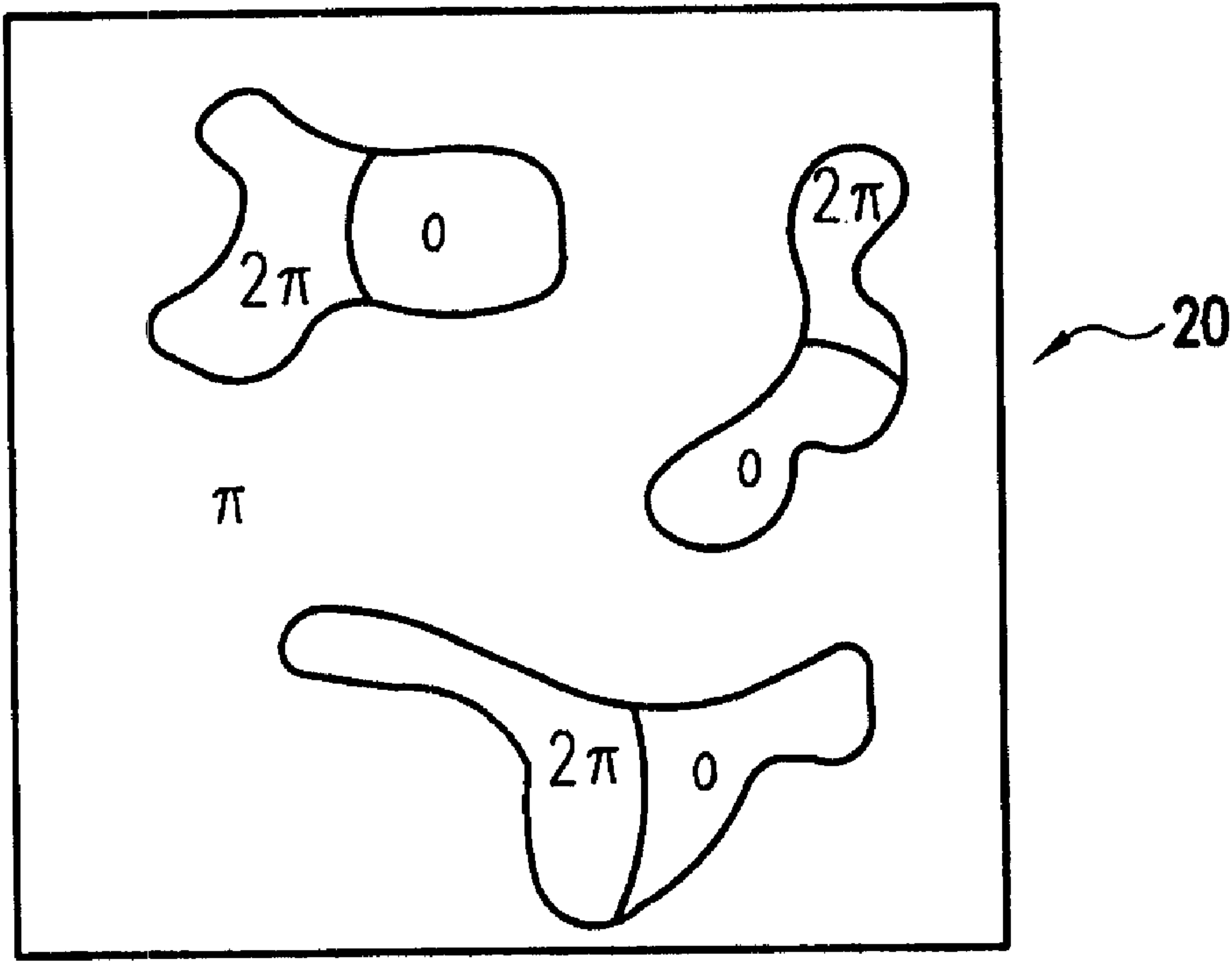
FIG.6A

λ < λo

FIG.6B

λ > λo

FIG.6C



2π
0
2π
π
0
2π
0
20