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Microwave kinoform for magnetic fusion

Neal C. Gallagher, Jr.
and
Donald W. Sweeney

Lawrence Livermore National Laboratory
Livermore, California 94550*

Abstract

A microwave kinoform that modifies both the phase and polarization of an incident wavefront has been designed. This kinoform for the TMX-U magnetic fusion experiment has been fabricated and tested. The design procedure, method of fabrication, and experimental test results are discussed.

Introduction

Microwave resonant heating has gained popularity as a means of depositing energy in the plasma for magnetic fusion experiments.¹ The coherent microwaves are produced by a gyrotron source whose output has been mode converted to the TE_{01} "doughnut" mode with an average power of 200 kW. Unfortunately, the doughnut mode does not provide ideal energy transfer to the plasma; there are two problems. The doughnut shape, with low field strength in the center and high field about the perimeter, is quite different from the desired Gaussian field envelope. In addition, the TE_{01} mode is linearly polarized such that the E-field vector is always tangent to the doughnut; vertical polarization is desired. Figure 1 contains an illustration of the initial gyrotron output wavefront and the desired wavefront at the target plane in the plasma; as can be seen, these are quite different patterns. In order to provide the transformation from the source pattern to the desired pattern, a microwave kinoform has been designed, fabricated, and tested. This kinoform is successful in transforming both the source field distribution and polarization into the desired patterns.

The kinoform is a computer-generated element that modifies only the phase of the incident wavefront.² Assumptions that are typically made for the design and utilization of kinoforms include scalar wave theory, Fresnel propagation, vertical (horizontal) polarization, and the thin element approximation. Our previous discussion of the gyrotron's TE_{01} mode polarization leads us to doubt the validity of the scalar theory assumption. In addition, the Fresnel approximation does not apply. It is possible, in a manner, to work around these problems. To aid in this understanding, Fig. 2 may be of help. The wavefront cross section and the size of the kinoform element are such that, when compared to the propagation distances, they do not allow the small angle assumption of the Fresnel approximation. Similarly, obliquity factors cannot be ignored. These assertions are verified by experimental results. In addition, beam polarization does affect propagation. Scalar theory may be accommodated by the independent propagation of the vertical and horizontal components from the gyrotron to the kinoform mirror. In this manner, scalar theory may be applied independently to each linear polarization component. In order to create pure vertical polarization for the entire field at the kinoform, a twist reflector is incorporated into the mirror surface of the kinoform³; the operation of the twist reflector is discussed later in the paper.

The result of these limitations is that we need to apply rigorous Rayleigh-Sommerfeld scalar diffraction theory to describe the respective propagation of the two field polarization components. We cannot make a thin element approximation because of the off-axis geometry and large size of the reflector (23 cm x 35 cm), and the vector theory of EM propagation is required to describe the function of the twist reflector. The relevant question is how do we design the kinoform with these restrictions?

The method we employ to design the kinoform is similar to an iterative algorithm first proposed by Hirsch, Jordan, and Lesem in a patent disclosure.⁵ As the method never appeared in the journal literature, it was subsequently reinvented by Gerchberg and Saxton⁶ and by Gallagher and Liu.^{7,8} A number of signal processing schemes have since evolved from this basic method.⁹

*The authors are on leave from Purdue University, West Lafayette, IN 47907.

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Figure 1. Doughnut shaped wavefront (left) needs to be transformed into a Gaussian shaped wavefront (right).

Figure 2. System geometry.

Kinoform design

The design procedure can be described with the help of Fig. 2. By starting with the known mode structure of the waveguide output and an initial guess for the mirror surface, the wavefront is propagated to the kinoform mirror surface. The vertical and horizontal polarization components are propagated independently. At the mirror surface, we assume that the twist reflector shifts the horizontal component into vertical polarization. This new vertical component is combined with the original vertical component so that now the entire field is treated as having pure vertical polarization with an intensity distribution as found in Fig. 3. The propagation is computed using the rigorous Rayleigh-Sommerfeld diffraction integral. Fast algorithms, such as the FFT, cannot be employed for this calculation. The iteration now begins. The field is propagated from the mirror surface to the target plane within the plasma, a propagation distance of about one meter. At this plane, the field has some desired intensity distribution; the phase distribution is not important. However, unless we have made an extremely lucky first guess for the mirror surface, the computed field intensity is not the desired field intensity. At this point in the procedure, we impose the desired intensity pattern. We keep the computed phase and then back propagate the field to the mirror surface. The phase distribution of this back propagated wavefront allows us to revise our initial guess for the mirror surface contour. Unfortunately, the field amplitude of this wave will no longer be the correct amplitude; i.e., the amplitude of the wavefront arriving from the source, as shown in Fig. 3; if it were the correct amplitude, the design would be complete. We now begin a new iteration. With the correct field amplitude of Fig. 3 and a new phase distribution imposed by the revised mirror, we again propagate to Plane 3. This process is continued until the propagated field intensity in the plasma is sufficiently close to the desired pattern. The procedure converges rapidly to the desired solution; typically, five to ten iterations provide an acceptable design.

Figure 3. Intensity of wavefront incident on kinoform reflector.

The function of the twist reflector cannot be described by use of scalar diffraction theory. It consists of a family of grooves cut into the mirror surface. The duty cycle for these grooves is approximately 50 percent. The period of the groove spacing is less than $1/2$ wavelength. The wavelength of our microwaves is about 1 cm. The grooves are cut to a depth of about $1/4$ wavelength. Suppose that polarized light strikes such a grooved surface and consider the E-field components that are respectively parallel and orthogonal to the groove orientation. The component parallel to the grooves reflects from the top of the grooved surface. The orthogonal component reflects from the bottom of the grooved surface. Because this component must travel to the bottom of the groove and back out again, a total phase shift of π is introduced on this component. The result being that the E-field has been "twisted" by the grooved surface. The twisting is such that at each point on the surface, the groove bisects the angle between the incident E-field and the reflected E-field. This is illustrated in Fig. 4. Because the polarization of the field is known at each point on the mirror surface, it is possible to compute the family of grooves that will twist the field at each point on the surface such that the field is everywhere vertically polarized. This groove pattern is shown in Fig. 5. When the grooves are actually milled into the mirror surface, special care must be taken to prevent adjacent grooves from intersecting. In addition, care must be taken to prevent the spacing between grooves from becoming too great; otherwise, the groove structures may act as diffraction gratings which is very undesirable. For our twist reflectors, the family of possible groove spacings is carefully sorted and grooves are turned "on" or "off" to prevent spacing problems (see Fig. 6).

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Figure 4. Relationship between incident E-field, twist grooves, and reflected E-field.

Figure 5. Twist reflector groove pattern.

Figure 6. Magnified view of twist groove structure. The diagram shows the centerline and edge lines for each groove. Note how the grooves turn "on" or "off" to keep proper spacing.

Kinoform fabrication and testing

A kinoform has been designed for the system illustrated in Fig. 2. The kinoform is designed to produce a Gaussian-like envelope as shown in Fig. 1. After eight iterations in the design procedure, a kinoform surface was computed that yields a plasma plane intensity envelope as shown in Fig. 7. This design produces an rms error of about 8 percent between the computed field and the desired field. It should be noted that kinoform phase is unwrapped before the surface profile is computed. This unwrapping avoids surface discontinuities produced with the modulo 2π phase values that are produced by the Rayleigh-Sommerfeld integral calculations.

Kinoform fabrication is accomplished on a Sundstrand computer-controlled five-axis milling machine. The five degrees of freedom for the machining tool are its x, y, and z position, as well as the two direction cosines for the angular orientation of the tool at the surface to be machined. The kinoform is machined in two steps. In the first step, the surface profile computed by the iteration procedure is milled into the surface. For the second step, the grooves of the twist reflector are milled into this mirror surface. The dimensions of the finished kinoform are approximately 23 cm x 35 cm. Nominally, the total milling time for both steps is about 20 hours; in practice, it has taken somewhat more time.

Figure 7. Plasma plane intensity envelope produced by Kinoform Design obtained after eight iterations.

After fabrication, the kinoform has been tested in a configuration similar to that found in Fig. 2. Figure 8 contains the measured field intensity contour profile for the desired polarization direction as found in the plasma plane. Figure 9 contains a plot of the undesired field polarization in the plasma plane. This test shows that about 95 percent of the field energy has the desired linear polarization. It also illustrates the Gaussian-like intensity profile that the kinoform is designed to produce. With respect to the waveguide source, we note that it has been estimated that gyrotron source output may be contaminated by up to 10 percent with modes other than the TE_{01} mode. This mode contamination will cause degradation in the kinoforms performance. However, if this mode contamination is known, the kinoform can be designed to accommodate these actual wavefronts. Figure 10 shows a photograph of the mirror being made. The tool for cutting the twist grooves can be seen in the corner.

Comments

There are a number of substantial differences between our iteration procedure and those employed in the past.^{5,6,7,9} First, we are propagating wavefronts over relatively small distances to and from three dimensional surfaces. This is very different from the image plane to Fourier plane type iteration employed in the past. In our procedure, the design surface is actually modified from iteration to iteration; this is different than simply altering the phase of the wavefront in one plane or the other. Because we are actually fabricating an optical element, it is important that phase values used in the surface design be unwrapped from their modulo 2π values. Also, because we are actually designing an element, it is important that the surface be smooth. Consequently, we have found it useful to smooth the kinoform surface with an averaging window at each step of the iteration; this aids in convergence to a smooth design.

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Figure 8. Experimental contour plot of field intensity for the desired polarization component.

As a final remark, we note that by using this method, it may be possible to design elements for infrared or even visible wavelengths. However, questions on sampling requirements and fabrication techniques need to be addressed.

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Figure 9. Experimental intensity measurements of undesired polarization component.

Figure 10. Kinoform being fabricated on five-axis mill.

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