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Fabrication issues for a chirped, subwavelength form-birefringent polarization splitter

S.A. Kemme, J.R. Wendt, G.A. Vawter, A.A. Cruz-Cabrera, D.W. Peters, R.R. Boye, C.R. Alford*, T.R. Carter*, S. Samora*

Sandia National Laboratories, Albuquerque, NM 87185-0603

*L&M Technologies, Albuquerque, NM 87123

sakemme@sandia.gov, Tele: 505-284-4639, Fax: 505-844-8985

ABSTRACT

We report here on an effort to design and fabricate a polarization splitter that utilizes form-birefringence to disperse an input beam as a function of polarization content as well as wavelength spectrum. Our approach is unique in the polarization beam splitting geometry and the potential for tailoring the polarized beams' phase fronts to correct aberrations or add focusing power. A first cut design could be realized with a chirped duty cycle grating at a single etch depth. However, this approach presents a considerable fabrication obstacle since etch depths are a strong function of feature size, or grating period. We fabricated a period = Λ = 1.0 micron form-birefringent component, with a nominal depth of λ = 1.7 microns, in GaAs using a CAIBE system with a 2-inch ion beam source diameter. The gas flows, ion energy, and sample temperature were all optimized to yield the desired etch profile.

1. INTRODUCTION

Subwavelength optical devices have been attractive for years as compact, integratable methods of manipulating optical field properties. However, it is only in the last few years that we have been successful in etching the high-aspect ratio structures necessary for components that are, for example, form-birefringent. We report here on an effort to design and fabricate a polarization splitter that utilizes form-birefringence to disperse an input beam as a function of polarization content as well as wavelength spectrum. Other approaches to realize polarization splitters, both traditional as well as diffractive, have been demonstrated previously [1-3]. These methods are inappropriate for this configuration primarily due to the geometrical layout of the components. Our approach is unique in the polarization beam splitting geometry and the potential for tailoring the polarized beams' phase fronts to correct aberrations or add focusing power. The fabrication challenges here include those encountered when manufacturing a form-birefringent waveplate: deep, subwavelength features with smooth, rectangular etch profiles. We and others have presented successes in this arena, where the spatial frequency is constant and the duty cycle may be optimized to produce a broad waveband device [4-6].

For this new component, the spatial frequency and/or the duty cycle is chirped to tailor the polarization dispersion and wavelength spread. A conceptual picture may be grasped by considering this device as a birefringent prism, where the TE, zero-order beam is transmitted at one angle (θ_{TE}) and the TM, zero-order beam is transmitted at another (θ_{TM}). The transmission angle, for each polarization component, is a function of the change in accumulated beam retardance as it passes through the device. To maintain plane wave transmission, the integrated retardance should increase linearly as we move laterally across the device. This is shown in Figure 1 for an incident plane wave at one wavelength.

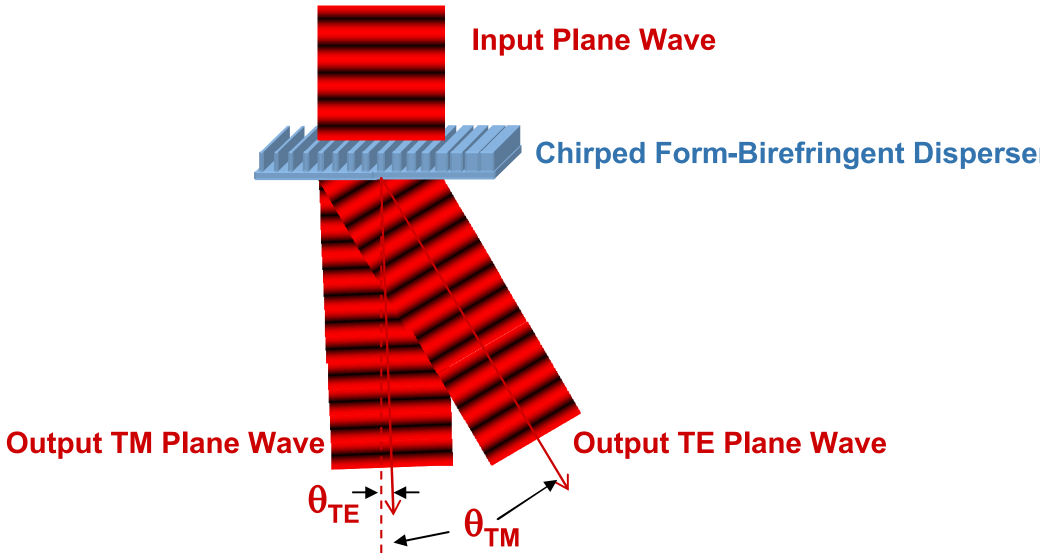

Figure 1 Layout of form-birefringent polarization disperser at a single wavelength.

Given the above conceptual picture, an ideal design could be realized with a chirped duty cycle grating at a single etch depth. However, this approach presents a considerable fabrication obstacle since etch depths are a strong function of feature size, or grating period. A typical fabrication result is illustrated in Figure 2 and Figure 3 where the grating period ranges from 400 nm to 4 microns, while the etched depth varies by more than a factor of two.

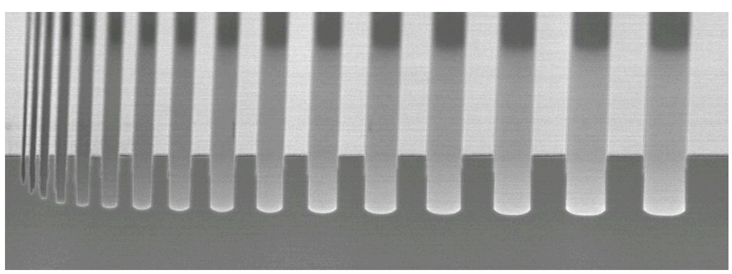

Figure 2 SEM of a chemically-assisted, ion-beam etched, chirped grating in GaAs. The period ranges from 400nm to 4 microns. The resulting etch depth ranges from 1.25 microns to 2.65 microns.

Fortunately, these fabrication constraints are not complete impediments because we have at least two parameters that affect the polarization and wavelength dispersion bands; namely the duty cycle and the grating period. These are varied in concert to maximize the transmitted deflection angle difference and/or to spread the spectrum as a function of transmitted angle. We simulate their effectiveness at the realistic depths imposed by the fabrication process. Moreover, because these two parameters (duty cycle and period) are defined lithographically, we are not limited to a linear additive phase delay. Instead we can tailor this phase delay to, for example, focus the transmitted and separated polarization components.

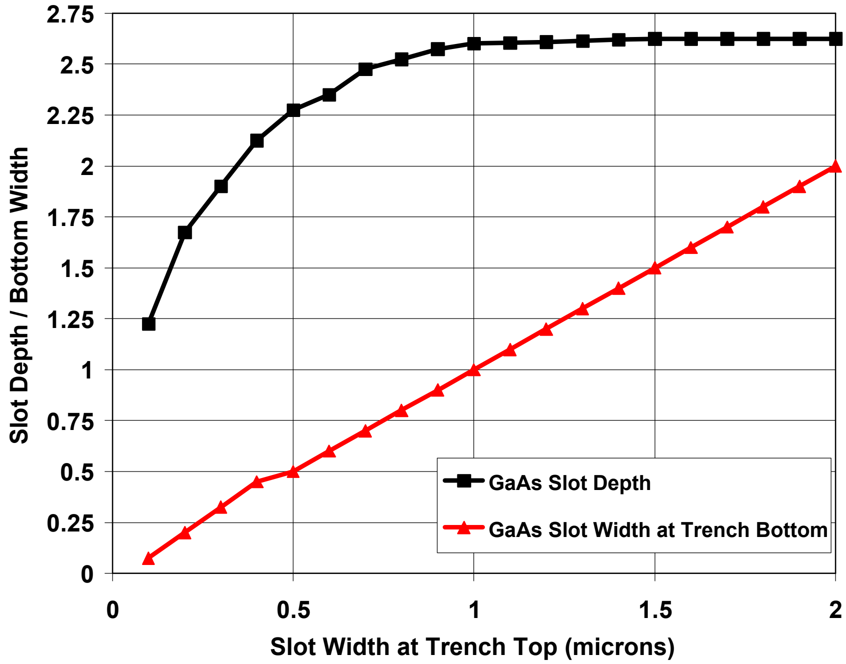

Figure 3 Measured etch depths and slot widths for the chirped grating in GaAs. The period ranges from 400nm to 4 microns. The resulting etch depth ranges from 1.25 microns to 2.65 microns.

2. ETCHING A FORM-BIREFRINGENT POLARIZATION SPLITTER

Fabrication of deep slots with subwavelength width and spacing presents a number of unique challenges. The need for slots of very high-aspect ratio with vertical walls dictates that a dry-etching process be used. The etch method must remove material from the bottom of the slot without removing material from the sides. Such anisotropic etching is accomplished with Chemically Assisted Ion Beam Etching (CAIBE) wherein the masked wafer is placed in steady flow of reactant gas (Cl_2 and BCl_3 in our case) and exposed to a highly directional beam of energetic Ar ions. The Ar ions will physically knock GaAs atoms out of the wafer surface causing a sputter etch following the directional nature of the Ar ion beam. The addition of a reactant gas to the wafer surface reduces the binding energy of the Ga and As atoms at the surface allowing for improved etch rates and control of the sidewall angle [7].

Early efforts to etch the high-aspect ratio features were limited by a significant proportion of energetic Ar ions that were not normal to the wafer plane. This resulted in the non-rectangular grating profiles seen in Figure 4. The maximum off-axis angle of these sputtering ions impacted the minimum width of a slot and ultimately the maximum achievable depth of the grating, since deep grating mesas would eventually etch through laterally.

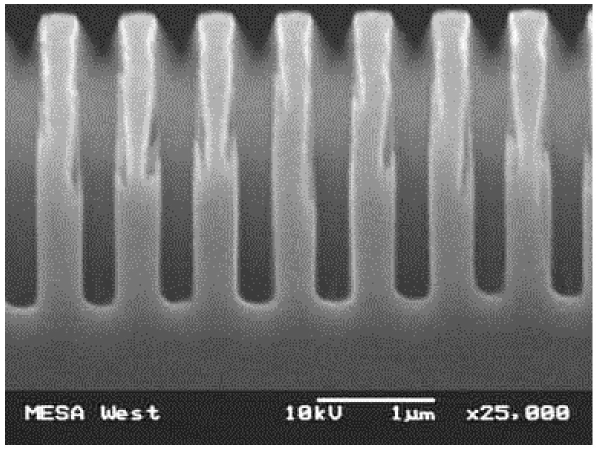

Figure 4 High-aspect ratio features in GaAs affected by off-axis angle etch species.

The above issue was mitigated by reducing the diameter of the etching beam; blocking primarily the higher-angle sputtering species. Clearly this reduces the uniformity over a large area. However, for smaller area components, the improved grating profile, shown in Figure 5, makes this option preferable. Grating duty cycles, smaller than 20%, do not have sufficient slot depth or uniformity. Grating duty cycles larger than 70 %, at these significant etch depth, are not mechanically robust enough to withstand post-etch processing. Thus the duty cycles between 20% and 70%, inclusive, are available as design parameters for a grating period of 1 micron.

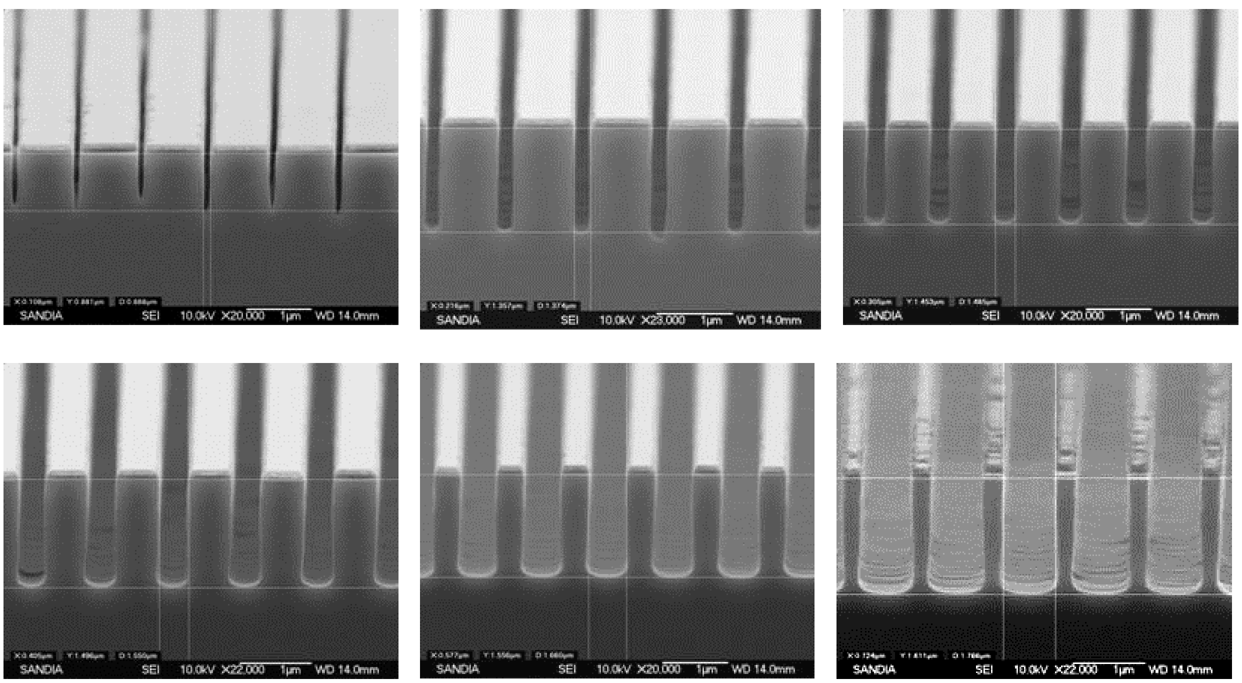

Figure 5 High-aspect ratio features in GaAs without off-axis angle etch species.

Figure 6 shows the new etch parameters, depth versus slot width at top, for a one micron period grating and for the optimized etch process. Excluding the data point for a slot width of 100nm (duty cycle of 10%), the grating depth now varies by less than 20% over the duty cycle range

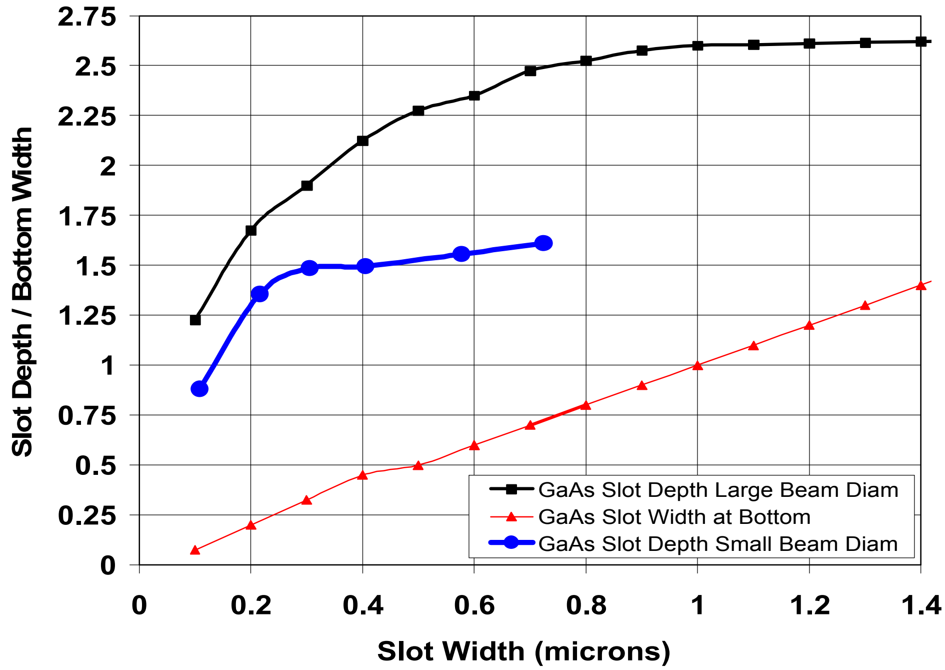

Figure 6 Measured etch depths and slot widths for the chirped grating in GaAs.

3. DESIGN OF QUASI-STATIC FORM-BIREFRINGENT POLARIZATION SPLITTER

Now that a range of reasonable grating depths and duty cycles can be fabricated, rigorous coupled wave analysis is utilized to identify a design for the form-birefringent polarization splitter.

We use the difference in the phase delays of the two polarizations, the retardance angle = $\varphi = \theta_{TM} - \theta_{TE}$, as a screening parameter. For a single input wavelength, this parameter should be large over a range of duty cycles. Figure 7 shows the retardance angle of a quasi-static, subwavelength regime device as a function of both wavelength and duty cycle. At a wavelength of $\lambda = 2$ microns, a usable duty cycle range would be $0.2<dc<0.6$. At the $dc = 0.2$ end of the component, the difference in the two delay angles is roughly 300 degrees. At the other end of the component, $dc = 0.6$, the difference in the delay angles is approximately 400 degrees. If the component and incident beam width are 100 microns, the then physical tilt between the two polarized beams is roughly 0.3 degrees.

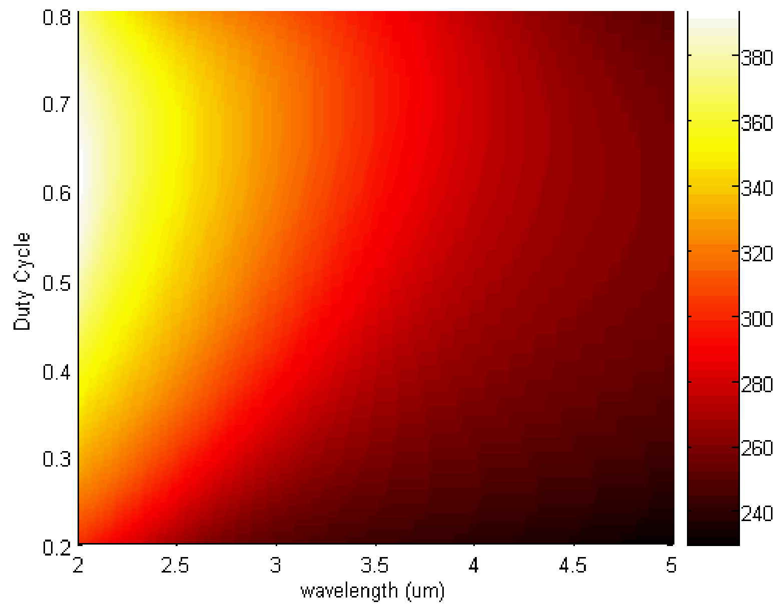

Figure 7 Retardance angle of a quasi-static, subwavelength regime device as a function of both wavelength and duty cycle. Period = 100nm, grating height = 1000 nm, input polarization is linear at 45 degrees.

4. DESIGN AND FABRICATION OF FORM-BIREFRINGENT POLARIZATION SPLITTER

The above numerical treatment is not realistic for a fabrication effort today since the period = 0.1 microns is so small. Instead, we need to utilize larger periods, near $\Lambda = 1$ micron, so that a range of duty cycles may be accessed. Now the retardance angle graph is more complicated; the retardance angle gradient curve loops back on itself as a function of wavelength and duty cycle, as in Figure 8.

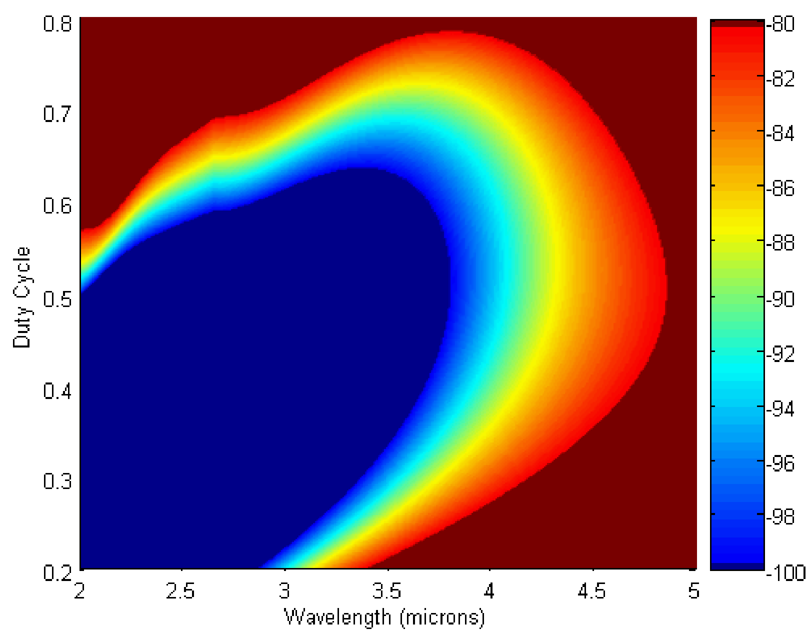

Figure 8 Retardance angle of a birefringent device as a function of both wavelength and duty cycle. Period = 800nm, grating height = 1100 nm, input polarization is linear at 45 degrees.

There are two distinctly different wavelength ranges and corresponding angular retardance responses. Comparing the two extremes of the fabricatable duty cycle range of 0.2 and 0.6 microns, we see at 3 microns that the retardance angle at these two extrema is 100 degrees. As we move to 3.75 microns, the retardance angle diverges between the two duty cycles. Note that at λ = 3 microns, the beams are coincident. On the other hand, as we move down in wavelength from λ = 2.75 microns to λ = 2 microns, the two polarization beams increasingly diverge, but in the opposite sense. That is, if the TM beam was on the right side when $3< \lambda <3.75$ microns, then it is on the left side when $2< \lambda <2.75$ microns. This response can effectively extend the useful wavelength range of the polarization beam splitter.

CONCLUSIONS

We report here on an effort to design and fabricate a polarization splitter that utilizes form-birefringence to disperse an input beam as a function of polarization content as well as wavelength spectrum. Our approach is unique in the polarization beam splitting geometry and the potential for tailoring the polarized beams' phase fronts to correct aberrations or add focusing power. A first cut design could be realized with a chirped duty cycle grating at a single etch depth. However, this approach presents a considerable fabrication obstacle since etch depths are a strong function of feature size, or grating period. Fortunately, these fabrication constraints are not complete impediments because we have at least two parameters that affect the polarization and wavelength dispersion bands; namely the duty cycle and the grating period. These are varied in concert to maximize the transmitted deflection angle difference and/or to spread the spectrum as a function of transmitted angle.

We fabricated a period of 1.0 micron form-birefringent component, with a nominal depth of 1.7 microns, in GaAs using a CAIBE system with a 2-inch ion beam source diameter. The gas flows, ion energy, and sample temperature were all optimized to yield the desired etch profile. Specifically, the sample was held at 50C while exposed to a reactant flow of 6 sccm Cl_2 and 1 sccm BCl_3. The Ar ion beam used was 20 mA beam current at 500 eV energy. The final etch depth of 1.77 um was achieved in 25 minutes etch time.

ACKNOWLEDGEMENTS

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