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**THE DEVELOPMENT OF A SPACE-WORTHY
FARADAY ROTATION AMMETER
FOR PLASMA CURRENT MEASUREMENTS**

by

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A DISSERTATION

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ABSTRACT

School of Graduate Studies
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Degree Doctor of Philosophy College/Dept. Physics
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for Plasma Current Measurements

This dissertation presents results of a program to develop a space-worthy Faraday Rotation Ammeter (FRA) prototype which, when launched into an auroral plasma, would directly measure the total ambient current in the plasma by detection of the current-induced Faraday rotation of highly polarized light travelling around a unique spun elliptically birefringent (SEB) fiber. The FRA provides a non-invasive, yet direct measurement of localized space plasma current densities, heretofore unavailable.

The nature of transmission through single-mode fibers, the effect of the wavelength of the light source and the effect of Rayleigh scattering within a fiber are combined here in a new model, along with the limitations of system components. This model predicts the minimum current to which the FRA system is sensitive and is used to evaluate the sensitivity of several FRA system designs.

Several novel FRA system designs were tested to determine the optimal design for removal of slowly varying fiber birefringence effects and were evaluated for space

flight on the basis of complexity, compact size, mechanical stability, and ease of operation. These evaluations and a new fiber design led to the prototype FRA design which is insensitive to mechanical and thermal perturbations of the fiber and is sensitive to plasma current densities as low as 7 mA/m^2 , less than two orders of magnitude above the expected plasma current densities. This is the smallest current density measurement achieved by a space-worthy optical fiber ammeter reported to date and the first sensitivity data from an FRA using an elliptical core SEB fiber. The prototype was integrated to a rocket, vibration and sequence tested, and launched into an aurora on March 6, 1994. Sensitivity data for the FRA prototype using the new elliptical core SEB fiber is included along with the optical, mechanical and electrical descriptions of the prototype.

A complete derivation of the retardance and Faraday rotation sensitivity for the newly designed SEB fiber is presented. Interpretation of these expressions is presented for a high-birefringent preform SEB fiber of sufficient length for a Faraday plasma current sensor. Also, new results of temperature sensitivity tests are presented which show that the elliptical core SEB fiber is an order of magnitude less sensitive to temperature variations than either a low birefringence twisted fiber or a bow-tie core SEB fiber.

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LIST OF SYMBOLS

<u>Symbol</u>	<u>Definition</u>
\vec{H}	Magnetic Induction
L_p	Linear Birefringence Beat Length
L'_p	Elliptical Birefringence Beat Length
L_t	Circular Birefringence Beat Length
n	Index of Refraction
NA	Numerical Aperture
$R(z)$	Linear Birefringence as a function of z
$V(\lambda)$	Verdet constant in rad/T·m
$V'(\lambda)$	Verdet constant in rad/A
α	Circular Birefringence in radians, unless specified
α^L	Circular Birefringence in radians per unit length
β	Linear Birefringence in radians, unless specified
β^L	Linear Birefringence in radians per unit length
$d\vec{l}$	Interaction Length for Faraday Rotation
η_c	Light Coupling Efficiency into a fiber
η_r	Responsivity of photodetectors in A/W
θ_F	Faradat Rotation Angle
λ	Wavelength
μ_0	Vacuum Permeability

ξ	Twist per Unit Length
χ	Extinction Ratio
χ_f	Extinction Ratio of a fiber
χ_P	Extinction Ratio of a polarizer
$\varphi(z)$	Principal Axis Orientation as a function of z
$\Omega(z)$	Rotation of the Principal Axis as a function of z

<u>Acronym</u>	<u>Definition</u>
AOM	Acousto-Optic Modulator
CW	Continuous Wave
DOP	Degree of Polarization
DSA	Digital Signal Analyzer
FFT	Fast Fourier Transform
FRA	Faraday Rotation Ammeter
GRIN	Gradient Index
LCR	Liquid Crystal Rotator
PBS	Polarizing Beam Splitter
SEB	Spun Elliptically Birefringent
SOP	State of Polarization
SRD	Super Radiant Diode

Chapter 1

INTRODUCTION

1.A Determination of Plasma Current Densities

The most commonly studied equation of the kinetic theory of plasma physics is the Vlasov equation

$$\frac{\delta f}{\delta t} + \vec{v} \cdot \nabla f + \frac{q}{m}(\vec{E} + \vec{v} \times \vec{B}) \cdot \frac{\delta f}{\delta \vec{v}} = 0$$

Here, the force acting on the particle is entirely electromagnetic, $f(\vec{r}, \vec{v}, t)$ is the velocity distribution function, and the plasma is sufficiently hot so that collisions can be neglected. The velocity distribution function describes, with seven independent variables, the number of particles per m^3 at position \vec{r} and time t with velocity components between v_x and $v_x + dv_x$, v_y and $v_y + dv_y$, and v_z and $v_z + dv_z$. Note, in particular, the intimate relationship between the electric or magnetic field and $f(\vec{r}, \vec{v}, t)$. Since the electric and magnetic fields depend on the position, \vec{r} , they both also depend on f ; but f is a function of position and, therefore, depends on the fields.

When plasma electrons drift with respect to plasma ions with an average speed higher than some threshold value, both the electrostatic and electromagnetic fields grow exponentially at the expense of electron kinetic energy, i. e. an instability occurs. The existence of a large field-aligned current during auroral substorm activities has led to speculation that this current may generate an instability which

may cause an anomalously large resistivity which could create a very large electric field parallel to the magnetic field [Hasegawa ?]. The upward-directed field-aligned current associated with auroras can be carried only by ions flowing upward out of the ionosphere and electrons flowing downward from the magnetosphere [Lyons and Williams ?]. The maximum field-aligned current that can be supplied by the ionospheric plasma is that obtained by counting all particles of a given charge with a component of velocity upward along the magnetic field and neglecting all particles with a downward component. For a plasma species with a Maxwellian distribution of density N , thermal energy K_{th} , charge q , and mass m , the current from the upgoing particles is

$$j_{max} = Nq \left(\frac{K_{th}}{2\pi m} \right)^{\frac{1}{2}}$$

Assuming densities associated with high latitudes and a temperature of 2000 K [Lyons and Williams ?]:

$$2.6 \times 10^{-9} < j_{max} < 2.6 \times 10^{-7} \text{ A/m}^2 \text{ for protons,}$$

$$6.5 \times 10^{-8} < j_{max} < 6.5 \times 10^{-7} \text{ A/m}^2 \text{ for O}^+ \text{ ions, and}$$

$$1.1 \times 10^{-5} < j_{max} < 1.1 \times 10^{-4} \text{ A/m}^2 \text{ for electrons.}$$

Typical intensities of the large-scale, field-aligned currents calculated from observations on low altitude satellites are $1 \mu\text{Amps/m}^2$ for both the upward and downward currents, and the upward currents associated with discrete auroras extend up to a few times $10 \mu\text{Amps/m}^2$ [Lyons and Williams ?]. Recent calculations based on radar spectral asymmetries in the presence of field-aligned currents in the topside ionosphere indicate current densities $> 100 \mu\text{A/m}^2$ (Foster [?]).

Measurement of space plasma current densities, along with information on particle densities, gives relative particle drift velocities which are necessary to determine the critical drift velocities at which the ionospheric plasmas become unstable. There

is, therefore, a need for a direct, model-independent and non-intrusive measurement of space plasma current densities. There has been no method so far of performing a direct measurement of these minute space plasma currents. Existing laboratory techniques for direct current measurements have not been attempted in space plasmas as they are expected to cause perturbations larger than the ambient currents to be measured and cannot achieve the required sensitivity. Therefore, these currents are generally derived indirectly from intrusive magnetometer measurements. In the method for derivation of currents outlined below from Primdahl [?], comprehensive assumptions about the spatial distributions of the magnetic fields have to be made. These assumptions could lead to large errors, but the knowledge about magnetospheric current flow is so essential to the understanding of magnetospheric physics that these risks have been taken.

The significance of the assumptions made for derivation of currents may be understood from Primdahl [?]:

“Polar cap horizontal ionospheric currents have long been inferred from magnetic perturbations of polar magnetograms [Friis-Christensen and Wilhelm, 1975 and references]. These analyses can only yield equivalent current systems, and additional information is necessary for determining the real currents. Recent polar cap electric field observations . . . indicate current systems that are not in agreement with the equivalent horizontal current systems deduced from local magnetic observations . . .

. . . It must be stressed that (1) all current densities determined from the rocket measurements are local in some sense, (2) that their validity rests upon relatively unrestrictive assumptions (no neutral wind and homogeneity over relatively small dimensions of ≈ 50 km), and (3) that

any disagreement between these local measurements and the ground-based observations undoubtedly reflects a breakdown in assumption over large dimensions (≈ 500 km).”

Typical plasma current density determinations presently follow one of the two techniques below, as outlined by Primdahl [?]:

From Ohm’s Law: The electrical conductivity tensor, σ_{ij} , is calculated from atmospheric and magnetic field models, electron density and temperature profiles. The ionospheric models and conductivity tensors are combined with dc electric field, $\vec{\mathbf{E}}$, measurements made along the rocket trajectory to calculate the current density $\vec{\mathbf{J}}$,

$$\begin{aligned}\vec{\mathbf{J}} &= \hat{\sigma} \cdot \vec{\mathbf{E}}, \text{ or} \\ J_i &= \sigma_{ij} E_j\end{aligned}\tag{1.1}$$

From magnetometer measurements: By measuring the total magnetic field, $\vec{\mathbf{B}}$ with either precession or flux gate magnetometers, the ionospheric current density is obtained from

$$\vec{\mathbf{J}} = \nabla \times \frac{\vec{\mathbf{B}}}{\mu_0}\tag{1.2}$$

To find $\nabla \times \vec{\mathbf{B}}$ or $\vec{\mathbf{J}}$, some additional assumptions about the geometry and spatial distribution of currents have to be made. These assumptions, however, may lead to large errors.

The only way to eliminate assumptions and obtain more accurate space plasma current density information is by using direct current measurement techniques, as opposed to the indirect methods described above. Direct measurement of the plasma currents will open up completely new areas of study which have been impossible so far (Torbert [?]).

The research described in this dissertation has concentrated on the development of a space-worthy instrument which, when launched into an auroral plasma, would directly measure the total ambient current in the plasma, independent of the characteristics of the distribution function or the \vec{B} field. The instrument detects the Faraday rotation of linearly polarized light which is induced in several turns of special optical fiber by the magnetic induction produced by the ambient plasma current. This instrument, a Faraday Rotation Ammeter (FRA), traditionally consists of (1) a linearly polarized light source focussed into single-mode optical fiber, which has been spooled onto a ring, and (2) a polarization sensing scheme which determines the amount of Faraday rotation experienced by the polarized light when current passes through the plane of the fiber ring, given by $I = \int \vec{H} \cdot d\vec{l}$ (see Figure ??). This Faraday Rotation Ammeter is the one sensing technique which promises to satisfy the sensitivity requirement of a direct measurement of plasma current densities. Its development provides the motivation for this dissertation.

Advantages of the FRA over other possible current detection schemes include:

- Nonintrusive measurement: The flow of photons around the fiber loops has negligible influence on the naturally occurring plasma currents, and a semiconductive encasement over the fiber loops can be used to remove any static charge buildup during the flight which may disturb the plasma current flow. The semiconductive encasement also serves to protect the fiber loops from high electric fields which can overwhelm the Faraday effect in the fiber. Of course, the design of a nonintrusive sensor is useless unless the spacecraft is also designed to be nonintrusive.
- No EMI: The FRA is impervious to electromagnetic interference from the spacecraft. The Faraday rotation is due only to current passing through the

Figure 1.1 **Basic Faraday Rotation Ammeter Layout**

plane of the fiber loops, i. e. only magnetic induction which add along the fiber length result in a Faraday rotation. Also, only extremely high electric fields will affect the sensitivity of the sensor.

- Resolution: The physical size of the fiber loops equals the spatial resolution of the sensor. The loop size can easily be made very small, < 1 meter, or can be made as large as the payload capacity of the launch vehicle will allow. Important plasma phenomena inside auroral arcs, over distances < 1 km, will be observable with the FRA.
- Vector measurements possible: The velocity vector of the launch vehicle can be used to interpret the direction of flow of current through the fiber loop making determination of current geometry feasible. Continuous readings of $\vec{H} \cdot d\vec{l}$ recreate the current vector. On a satellite, three loops could be deployed in an

orthogonal configuration to determine the current field vector.

- Calibration: Calibration of the FRA is accomplished, even in flight, by passing a current carrying wire through the loop or a large solenoid around one fiber end.

The FRA is based on the magneto-optical effect in glass optical fibers. Currents from several kiloamperes to megaamperes have been routinely measured in some high-voltage transmission lines and monitoring applications (Veaser [?], Papp [?]) with traditional FRAs, but expected plasma current densities in the Earth's magnetosphere only range from 1-100 $\mu\text{A}/\text{m}^2$. The challenge is, therefore, to make accurate direct measurements of space plasma current densities of a few $\mu\text{A}/\text{m}^2$ by improving a technique traditionally used to measure currents of several megaamperes per square meter.

1.B The Faraday Effect

Michael Faraday, in 1845, discovered that the polarization of light is affected by a magnetic induction aligned along the length of the interaction medium. The phenomenon is called the Faraday effect. If the light is linearly polarized as it enters the medium, the plane of polarization undergoes a rotation as the light traverses the dielectric material in the presence of the magnetic induction. The angle of rotation, θ_F , caused by the Faraday effect is given by

$$\theta_F = V \int_L \vec{\mathbf{H}} \cdot d\vec{\mathbf{l}} \quad (1.3)$$

where $d\vec{\mathbf{l}}$ is along the propagation direction of the light beam, L corresponds to the length of the interaction medium, $\vec{\mathbf{H}}$ is the strength of the magnetic induction and V is the Verdet constant which is a measure of the magnitude of the magneto-optic

interaction. V is characteristic of the material and depends on the frequency ν of the incident radiation (see Chapter ?? Section ??).

The Faraday effect is different from other causes of optical activity in fibers such as twist and bend anisotropies. All causes of optical activity other than the Faraday effect are reciprocal, i. e. the net rotation of the state of polarization (SOP) is zero when light travels forward and back through the same material. The Faraday effect is non-reciprocal. The rotation on the reverse propagation path is additive to that of the forward propagation, because the magnetic induction direction is opposite to the reverse propagation vector. It is therefore possible to obtain a rotation of $N\theta_F$ by reflecting N times back and forth in the same length of interaction medium. For a closed path L with N turns, Ampere's law shows the rotation θ_F to be given by

$$\theta_F = NV'I \quad (1.4)$$

where V' , in convenient units of rad/Amp, is $\mu_0 V$, with μ_0 as the vacuum permeability. For silica optical fibers, V' is on the order of 1×10^{-6} rad/Amp (see Chapter ?? Section ?? for further details).

1.C Previous Fiber-Optic Ammeters

Optical fiber was first employed for measurement of current in 1978 (Smith [?]) followed by others (Rashleigh [?]). The lengths of fiber employed in these measurements were, typically, a few meters and were wrapped into rings with many hundreds of turns. This length was sufficient for the measurement of current magnitudes on the order of kiloamps or larger, which made these sensors useful to the power industry. The radii of the fiber coils were on the order of a few cm, large enough to allow a current carrying conductor to pass through. The traditional measurement (see Chapter ?? Section ??) is a response function proportional to $\sin(2NV'I)$ where I is the current through the plane of the loop of fiber, N is the number of fiber turns

and V' is the Verdet constant described above. Due to the small radii and short fiber lengths, the fibers in these sensors were fairly insensitive to environmental effects.

Developers of these power industry sensors have used different types of single-mode optical fiber including low birefringence fiber, spun high birefringence fiber, doped fiber and fiber which has been twisted by hand or machine before spooling. The most common type of fiber used in power industry FRAs is the twisted low birefringence fiber. Recent developers of these sensors (Laming [?], Li [?, ?]) have used a spun, high birefringence, bow tie core fiber designed to be insensitive to mechanical perturbations to which other fibers are particularly sensitive. The spun, high birefringence fiber was found to be unsuitable for the power industry needs due to the high bend-induced birefringence incurred in the winding of small rings.

In order to achieve the high current sensitivity required for measurements of extremely small plasma current densities, large diameter rings with many turns and, consequently, much longer lengths of fiber must be employed. Environmental effects such as temperature variations and vibrations are no longer small effects and must be eliminated by whatever means possible. A first attempt at a space-worthy FRA by I. Saxena [?] produced a system sensitive to 3 Amps/m² with large drifts due to temperature variations and mechanical perturbations of the fiber. Saxena quantified the drift due to temperature variations for low birefringence fibers with a fast ellipsometer. For the development described in this dissertation, a new fiber was designed and tested and several FRA prototype designs were investigated which would remove such environmental effects and also provide the sensitivity required to measure the plasma currents in an aurora. These efforts are described in the following chapters.

1.D Structure of the Dissertation

An understanding of the fiber, source and detector behavior in the measurement system of the FRA is necessary to determine the required operational conditions under which maximum precision can be achieved. The first flight-worthy FRA launched into an auroral plasma has been shown to be capable of detecting current densities as low as 6 mA/m^2 with 21 turns of optical fiber in a 9.6 meter diameter ring, a factor of 15 times per turn of fiber better than the previous attempt by Saxena [?] which was limited to 3 A/m^2 with 697 turns of optical fiber on a small ring. The relationship between the minimum detectable plasma current that the FRA can measure and the constraints of the measurement environment has been determined and modelled. These relationships are described in Chapter ??, the constraints of the measurement environment are described in Chapter ??, and a minimum current calculation is performed for the flight-worthy prototype in Chapter ?? and closely predicts the actual calibrated response of the FRA prototype.

This dissertation presents, in logical order, the experiments and theory leading to the integration of the flight-worthy prototype FRA to a sounding rocket for plasma current measurements. The factors governing the choice of wavelength operation and subsequent limitations to system sensitivity are outlined in Chapter ?. The constraints of the space environment and the sounding rocket are outlined in Chapter ?.

A new fiber was designed, tested, and, ultimately, incorporated into the FRA flight prototype. Chapter ? describes the theory behind spun fibers, the sensitivity of spun fibers to the Faraday effect, the design process for the new spun fiber, and the test results on that fiber. The theory and initial test data on the fiber was presented as a poster paper entitled “Theory of Retardance and Faraday Effect Sensitivity for Spun Elliptically Birefringent Fiber” [?]. The new spun, high birefringence, elliptical

core fiber was designed to be insensitive to mechanically induced linear birefringence to which other fibers are particularly sensitive and was expected to be insensitive to temperature fluctuations. This fiber was tested against the most common type of fiber used in power industry FRAs, the twisted, low birefringence fiber. The twisted fiber is extremely sensitive to temperature variations due to residual linear stress birefringence and is also sensitive to mechanically induced linear birefringence. The new spun fiber's response to current was not adversely affected by mechanical perturbations, as the design intended, or by temperature variations. It was found to be an order of magnitude less sensitive to temperature than a previously designed spun, high birefringence, bow tie core fiber (Laming [?]).

Descriptions and results of experiments with several novel FRA system designs are described in Chapter ???. These novel systems were designed to remove slowly varying linear and circular birefringence effects which interfere with current measurements in the traditional FRA. The designs were also evaluated to determine the best design for a sounding rocket flight. Designs were compared on the basis of complexity, compact size, mechanical stability, ease of automatic operation, and, of course, sensitivity to Faraday rotation. Components of the various designs were also optimized to reduce electro-optic noise sources. A combination of system design and new fiber design led to the final flight prototype FRA which had the best Faraday response and was the most mechanically stable for a rocket flight. Chapter ??? includes a description of the prototype's mechanical, optical and electrical design, a calculation with the new prediction model of its expected minimum current sensitivity, and the results of minimum current sensitivity tests of the prototype with the new spun fiber.

Finally, a summary of the research covered by this dissertation and suggestions for further research are included in Chapter ???.

"Include" fields for new chapters go here. Be sure to change the field properties to reflect the appropriate filename (e.g., "chap1" vice "intro").

APPENDICES

APPENDIX A

PREDICTION MODEL

The printout shown below is from the noise floor prediction model. The model calculates a minimum current sensitivity of 4.7 Amps for the flight prototype FRA1, with 21 turns of SEB fiber, 100 Hz bandwidth, and a surface reflection from the fiber face. This minimum sensitivity converts to 65 mAmps/m² of current density in an auroral plasma with the 9.6 m diameter loop of the prototype.

Noise Floor Prediction Model

Figure A.1 **Noise Floor Prediction Model**

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