Endless Tracking Polarization Controller

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ABSTRACT As a technology for increasing the capacity to meet growing communications demand in recent years, dense wavelength-division multiplexing (D-WDM) is being implemented in tandem with achieving higher transmission rates on each channel. At next-generation transmission rates of 40 Gbps, polarization mode dispersion (PMD) is thought to be the main factor in the deterioration of transmission characteristics. There is thus a need for endless tracking polarization controllers as constituents of PMD compensators. Here we report the development of an endless tracking polarization controller using variable Faraday rotators (VFRs), which offers superior optical characteristics and the promise of higher reliability.

1. INTRODUCTION

In response to the need for larger capacities in long-haul optical digital transmission, greater channel density has been achieved by wavelength division multiplexing (WDM), and the bit rate for each channel is also being increased.

At 40 Gbps, which is in the next generation of transmission rates, polarization mode dispersion (PMD), which does not present a problem at bit rates of 10 Gbps and below, can impose significant limitations on the distance over which transmission is possible. Further, at the distances served by 10-Gbps transmission, which is currently becoming the mainstream technology, there are concerns that using fibers installed in previous years may, depending on the amount of PMD, cause problems in terms of system configuration.

In recent years there have been many programs to study PMD compensators [1)~3)]. In PMD compensators, however, changes in distributed birefringence--induced either by increasing the core eccentricity of single-mode fibers or by means of internal stress due to changes in lateral pressure or temperature--give rise to a phenomenon known as differential group delay (DGD), in which two orthogonal polarization modes, which should, in theory, be degenerating in fact diverge.

In PMD compensators, a polarization controller is required to track changes in polarization due to distributed birefringence in the transmission path [1)~3)]. These changes in polarization are, due to variations in the transmission path environment, random with respect to time, with the result that in order to maintain the compensated state, it is necessary that the polarization controller track continuously all changes in polarization without becoming saturated (referred to in this paper as “endless tracking”). In particular, when a phase shifting device is used, attention must be paid to its control due to the limited range of phase shifting, a problem that has already been investigated [4),5)]. In wave plates that are mechanically rotated or waveguide-type polarization controllers using Lithium niobate (LN), which move in an equivalent manner [6)], it is the optical axis (eigen polarization axis) that is rotated, rather than the phase shift, so that there is no need to pay attention to saturation, but there are problems with the response speed in the former case and optical characteristics in the latter.

Phase-shifting devices can all be configured in the fiber, and fiber squeezers having superior optical characteristics have been widely studied in the past [4),5)], but since they apply direct lateral pressure to the fiber they raise the problem of reliability as an in-line device.

Accordingly we report the development of an endless tracking polarization controller using variable Faraday rotators (VFRs), which offers superior optical characteristics and the promise of higher reliability. In the process of device design, it was necessary to investigate two issues: (1) whether the range of phase shifting of the VFR, being less than that of the fiber squeezer, was adequate or not; and (2) the control method and tracking stability. However, it is difficult to investigate these two issues if some of the polarization conversions of the polarization controller are only discussed as examples on the Poincare sphere, as in previously published work. In the present work, we used expression [7)] of the rotation group to express the polarization conversion itself, and since we presented a mathematical treatment of the two issues above, we will also report on our methodology.

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2. POLARIZATION CONTROLLER USING VFRs

Table 1 ranks the main characteristics of the optical devices that constitute a polarization controller.

Lithium niobate (LN), as also used in modulators, is capable of operating at response speeds in the sub-microsecond order, but its insertion loss and PDL are greater than the other devices. Liquid crystal has a slow response speed (millisecond order) and generally has problems with respect to reliability. The fiber squeezer applies lateral pressure to the fiber directly by means of a piezoelectric device, and as an all-fiber device has extremely low insertion loss, but there are problems in achieving reliability for the stress applying section.

The variable Faraday rotator, on the other hand has an adequate response speed of several hundred microseconds, and since it comprises a garnet crystal, it can provide optical characteristics (insertion loss, PDL, etc.) and levels of reliability that are of the same order as conventional passive modules, and therefore constitutes a more balanced polarization controller than the alternatives.

Figure 1 shows the operating characteristics of the VFR. As shown in Figure 1a), the VFR of itself is, so to speak, a variable circular phase shifter that causes the polarized light to rotate. On the Poincare sphere it possesses a rotating function with the S3 axis as the axis of rotation, but with this alone, arbitrary polarization conversion is impossible. But by arranging 1/4 wave plates (QWPs) before and after the VFR so that their optical axes are orthogonal (see Figure 1b)), it becomes possible to configure a variable linear phase shifter that can vary the phase difference between orthogonal linear polarization modes. This can be easily understood if the Jones matrix for this configuration is analyzed. A variable linear phase shifter having the arrangement of optical axes shown in Figure 1b) will have the function of rotating on axis S2 on the Poincare sphere.

By combining these variable circular phase shifters and variable linear phase shifters alternately in multiple stages, it becomes possible to configure a polarization controller having an arbitrary conversion function and the capability of endless tracking.

This phase shifting capability is the result of varying the magnetic field applied to the garnet crystal using a magnetic circuit. The phase shifting range of VFRs currently in use is π, or 2π in terms of the angle of rotation on the Poincare sphere. In the discussion of the polarization controller using fiber squeezers previously referred to [4),5)] 4π is held to be necessary, and it is necessary to investigate whether a device using VFRs can provide endless tracking in the shifting range, and whether its stability is adequate.

Table 1 Optical devices that constitute a polarization controller.

	Liquid crystal	Fiber squeezer	LN	VFR
Response speed	△	○	◎	○
Reliability	△	△	○	○
Insertion loss	○	◎	△	○
PDL	○	○	△	○

Notes ◎: Superior ○: Satisfactory △: Fair

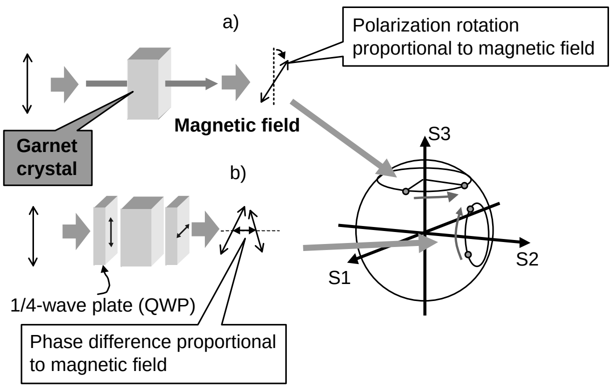


Figure 1 Operating characteristics of VFR.

3. ANALYSIS OF POLARIZATION CONVERSION BY ROTATION-GROUP PARAMETERS

3.1 Representing Polarization Conversion in Parameter Space

It is well known that light in the fully polarized state can be represented as a point on the Poincare sphere, and polarization conversion can be thought of as a path from point to point. Thus it is easy to understand polarization conversion intuitively by following the paths actually traveled by light sequentially as trajectories on the Poincare sphere, but there are an infinite number of such trajectories and they depend on the polarization state of the input light. Reaching a systematic understanding of the conversion structure configured by a polarization controller requires an understanding of polarization conversion as a rotational conversion from point to point on a Poincare sphere. That is to say, a polarization controller is a collection of rotational conversions made by the variable parameters (phase, eigen axis angle), and these are understood mathematically as a rotation group [7)].

This can be confirmed by the fact that the Jones matrix generally used in calculations of polarization corresponds to a two-dimensional representation (unitary matrix) of the rotation group. That is to say the Jones matrix may generally be given as

$$U = \begin{bmatrix} a & b \\ -\bar{b} & \bar{a} \end{bmatrix} \qquad \bar{a}a + b\bar{b} = |a|^2 + |b|^2 = 1 \tag{1}$$

Since a and b here constitute complex numbers, we may restate for $a = \kappa - i\nu$ and $b = -\mu - i\lambda$, yielding

$$U = \kappa\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} - i\lambda\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} - i\mu\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix} - i\nu\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

$$= \kappa E - i\lambda S_1 - i\mu S_2 - i\nu S_3 \qquad \kappa^2 + \lambda^2 + \mu^2 + \nu^2 = 1 \tag{2}$$

where: S_1, S_2 and S_3 are Pauli spin matrices.

As will be understood from Equation (2), all polarization conversions may be defined in terms of four parameters (κ, λ, μ and ν) forming a Jones matrix, and the functions of the polarization controller are determined by the range of values of these parameters, or, in other words, by the size of the subgroup.

The relationship between the four parameters above (κ, λ, μ and ν) and rotation in Stokes space may be expressed as

$$\kappa = \cos\frac{\omega}{2}, \lambda = \alpha\sin\frac{\omega}{2}, \mu = \beta\sin\frac{\omega}{2}, \nu = \gamma\sin\frac{\omega}{2} \qquad (3)$$

where: α, β and γ indicate the orientation of the axes of rotation, and ω indicates the angle of rotation.

The parameter space shown in Figure 2 is introduced for the sake of a visual presentation of the range of subgroups of the polarization controller. That is to say, using λ, μ and ν as a basis for the totality of polarization conversions shown in Equation (2), it is represented by two 3-dimensional spaces distinguished by the sign of κ. In such a case, we can see from Equation (3) that the totality of polarization conversions can be expressed by two spherical surfaces extending over the two 3-dimensional spaces and the points within them. (spheres **S** and **S'** are connected by surfaces). Since this expression is a representation of conversion itself, it makes possible both the direct visualization of the conversion structure made by the polarization controller, and a discussion that need not take account of the input polarized light.

Using this parameter space we delineate in the following the conditions for satisfying arbitrary conversion and endless tracking, for the purpose of discussing whether the former is possible, and the latter is stable.

3.2 Conditions for Arbitrary Conversion

Let us first consider a single set of input and output polarized light. In Figure 3a) input polarized light S_{in} and output polarized light S_{out} are defined in Stokes space. It will be understood that the rotational conversion at which $S_{in} \rightarrow S_{out}$ is realized is the totality of conversions having an axis of rotation (α, β and γ) facing toward the orientation on great circle C intersecting the mid-plane of S_{in} and S_{out} and the Poincare sphere, and having the angle of rotation

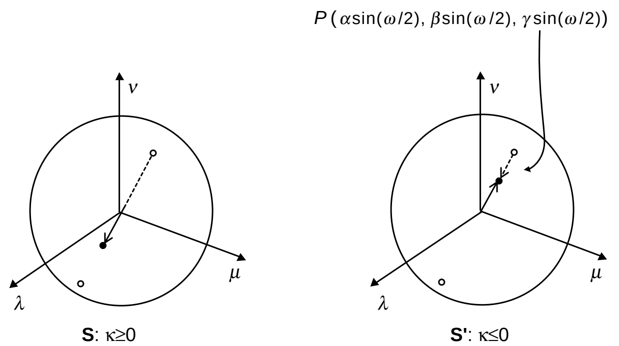


Figure 2 Parameter space.

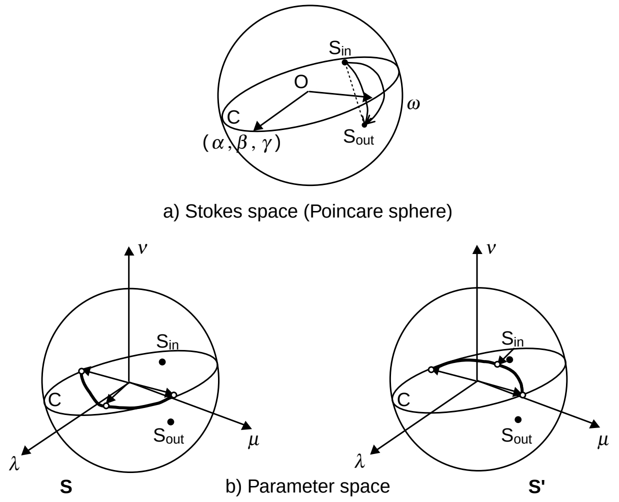


Figure 3 Conversion corresponding to a pair of input and output polarization states.

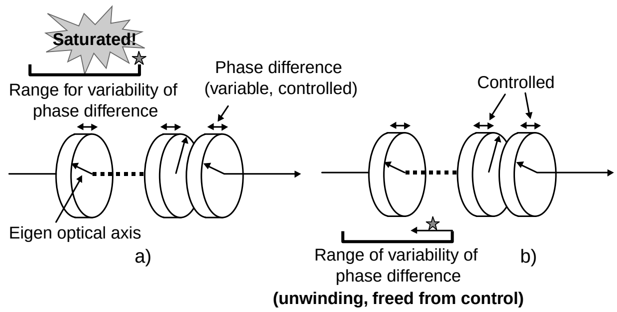


Figure 4 Control procedure for endless tracking (unwinding).

required for $S_{in} \rightarrow S_{out}$. Figure 3b) shows this as parameter space.

From Figure 3b) it will be understood that the collection of conversions that realize $S_{in} \rightarrow S_{out}$ is a closed curve extending over **S** and **S'** (an ellipse of which the orientation at the mid-point of S_{in} and S_{out} is the major axis). In effect, to realize $S_{in} \rightarrow S_{out}$, it is sufficient that the subgroup of the polarization controller intersect with the ellipse representing $S_{in} \rightarrow S_{out}$ at at least one point.

Since arbitrary conversion is the function of realizing all $S_{in} \rightarrow S_{out}$, the subgroup of the polarization controller intersecting with all ellipses at at least one point constitutes the condition for whether arbitrary conversion is possible or not.

3.3 Conditions for Endless Tracking

Before discussing whether endless tracking is possible or not, we will set forth a control method that avoids saturation using a phase-shifting device with a limited range of phase shifting. Figure 4 shows the control procedure.

First of all, the phase shifting devices are so arranged as to be orthogonal alternately to the eigen optical axes, and the phase difference of each device is controlled within the range of variability. If one of these reaches the limit of the range of variability (e.g. reaches the maximum phase difference as shown in Figure 4a)), that device can no longer move in a direction such as to further increase the phase difference. Accordingly the device must be freed from normal control and must "unwind" in the direction of the center of the range of variability of phase difference. See Figure 4 b). Since this unwinding operation will obviously affect the polarization state of the output light, the amount of unwinding is decreased and the amount of variation in polarization caused by it must be compensated for by the other phase shifting devices. In other words, to enable endless tracking even when a phase shifting device becomes saturated, it is necessary that arbitrary conversion be realizable using several stages other than the unwinding stage.

If we consider the condition for endless tracking in terms of parameter space, it is that the subgroups formed by the remaining devices continue to intersect with all ellipses (satisfy the conditions of arbitrary conversion), when the phase differences of the various phase shifting devices that make up the polarization controller are forcibly changed, i.e., unwound.

4. CONFIGURATION OF AN ENDLESS TRACKING POLARIZATION CONTROLLER

4.1 5-stage Polarization Controller

In a configuration comprising two phase shifting devices, it is obvious that when one of them saturates, only the remaining one can be controlled, and the conditions for endless tracking are not satisfied. Not only that, but, if the subgroups are represented in parameter space, even the conditions for arbitrary conversion are not satisfied. Thus to realize arbitrary conversion it is necessary to have at least three phase shifting devices, the eigen axes of which are orthogonal to each other. Even when using a VFR with range of phase shifting π, the same will be obvious using a parameter space analysis. It is also possible using reflection to configure an arbitrary polarization controller using two VFRs [8].

Thus to provide the function of endless tracking it is necessary to have at least four phase shifting devices--three for arbitrary conversion and one to compensate for the unwinding. With four devices, however, the unwinding operation is complicated, and it is recommended that five phase shifting devices be used [4),5)].

Let us then consider first a 5-stage polarization controller using VFRs. Figure 5 shows the configuration of a 5-stage polarization controller using VFRs. The operational characteristics of the constituent parts are as previously described in Section 2.

In the example shown here, we see that when one of the four VFRs other than the one in the center unwinds, three or more VFRs in the remaining section can effect arbitrary conversion, so that unwinding operation can be provided. The result of calculations of the subgroups produced by the four remaining VFRs when the center one unwinds are shown in Figure 6. Figure 6 shows the subgroups formed by the angle of rotation of the other VFRs

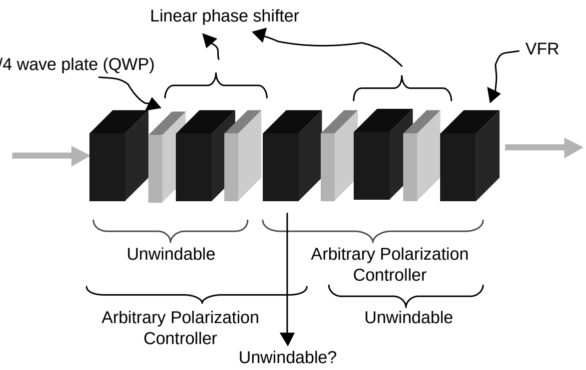


Figure 5 5-stage polarization controller with VFRs.

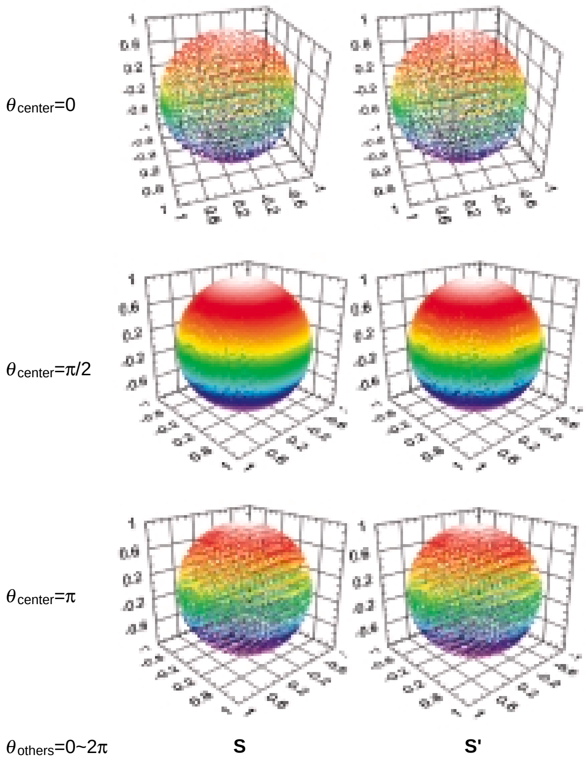


Figure 6 Subgroups during unwinding at the center VFR.

0~2π when the angle of rotation θ_{center} in Stokes space due to the center VFR is fixed.

From Figure 6 it will be seen that the center VFR is also capable of unwinding, and it will be seen that, in effect, in a polarization controller of the configuration shown in Figure 5 all VFRs are capable of unwinding, so that endless tracking is possible.

In the foregoing discussion, however, only one VFR is capable of unwinding, and it is not possible for two or more VFRs to unwind simultaneously. This polarization controller must therefore be controlled in such a way that only one VFR provides unwinding, and this places limitations on the stability of the polarization controller.

That is to say when two VFRs exceed the limits of the range of variation of phase shifting, only one is permitted to provide unwinding operation, and it is therefore possible that the two VFRs will hand off unwinding operation to

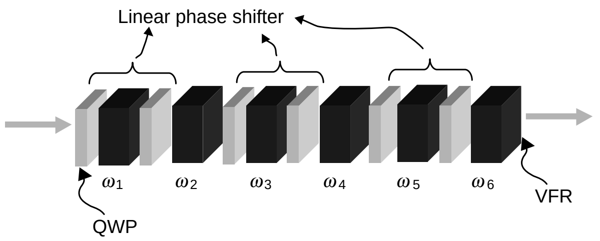
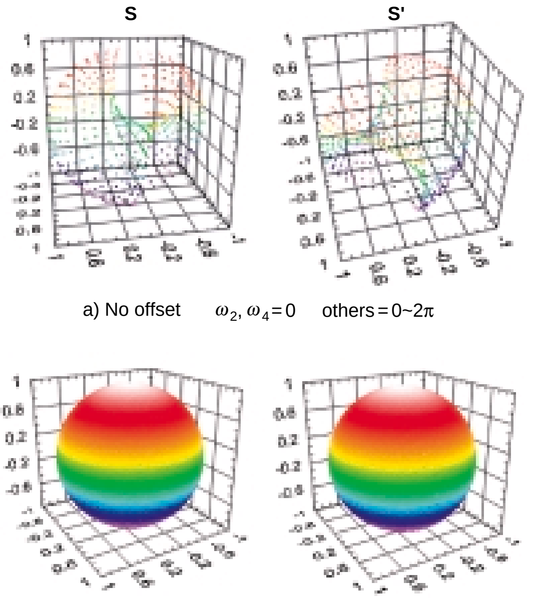


Figure 7 6-stage polarization controller with VFR.



a) No offset $\omega_2, \omega_4 = 0$ others $= 0 \sim 2\pi$

b) With offset $\omega_2, \omega_4 = \pi/4$ others $= \pi/4 \sim 9\pi/4$

Figure 8 Simultaneous saturation of two VFRs.

each other, remaining at the extremity of the range. In such a case there will be conversions that the polarization controller cannot cover, and tracking stability will be lost.

4.2 6-stage Polarization Controller

At first sight, it might be proposed, as a means of improving stability, that the range of phase shifting be increased thereby reducing the chance of reaching its limits, but for the VFRs currently in use this is not desirable, given the design of the magnetic circuit. Accordingly it was decided to configure a polarization controller with one more VFR. Figure 7 shows the 6-stage configuration.

Let the angles of rotation in Stokes space for each of the VFRs be ω_i, where i is from 1 to 6. At such a time there are a number of possible combinations of two VFRs causing a problem when saturating simultaneously, and Figure 8 shows the subgroups that can be formed at the remaining VFRs when ω_2 and ω_4 reach the minimum phase difference and saturate. Two cases are shown: with no offset applied to the range of variability of the angle of rotation, and with an offset of $\pi/4$.

According to Figure 8, when no offset is applied to the variable range of the angle of rotation, the conditions for arbitrary conversion are no longer satisfied and it is impossible to perform tracking with respect to the conversion of specific input and output of polarized light. When considered in the way described below, it is an obvious result. In other words since saying that the angles of rotation of ω_2 and ω_4 are 0 means that no conversion is performed, with the result that ω_1 through ω_5 are equivalent to a continuum of five linear phase shifters, and since this is the same as a single linear phase shifter, it in effect functions only like a 2-stage polarization controller. Arbitrary conversion is therefore impossible. When, on the other hand, an offset is applied, parameter space is filled, and the conditions for endless tracking are satisfied. The above has also been confirmed for other combinations of two VFRs.

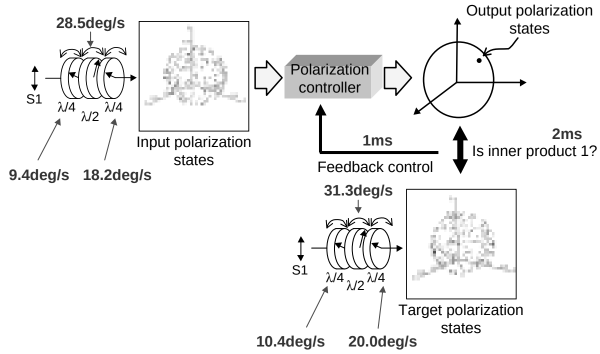


Figure 9 Configuration schema of simulation.

In the final analysis it will be understood that by using a 6-stage configuration and also applying an offset, it is possible to allow two VFRs to saturate simultaneously, thereby improving tracking stability.

4.3 Simulation

Simulations were conducted to verify the conclusions arrived at up to this point, and Figure 9 shows the schema used.

Arbitrary polarization of the input light was produced in a configuration consisting of a 1/4 wave plate, 1/2 wave plate and 1/4 wave plate, rotating at speeds of 9.4, 28.5 and 18.2 deg/s respectively. This light was input to a polarization controller having the configuration shown in Figure 7, and each VFR was subjected to sequence control. The polarized light output from the polarization controller was then compared with an arbitrary target polarized light produced in the same way as the input polarized light (speeds of 10.4, 31.3 and 20.0 deg/s respectively), and feedback was applied to the polarization controller so that its inner product was 1. The times allocated to calculation and comparison of the inner product and to feedback control were 2 ms and 1 ms respectively.

For each of the VFRs 1 step was set at 5.73 deg, while an unwinding step was 1.15 deg. Only one VFR would unwind, and when another VFR saturated while one was unwinding, the VFR that saturated later was unwound while the first VFR to unwind was returned to normal control.

Figure 10 plots the points at which the value of the inner product was 0.95 or less over a 4-hour period of tracking

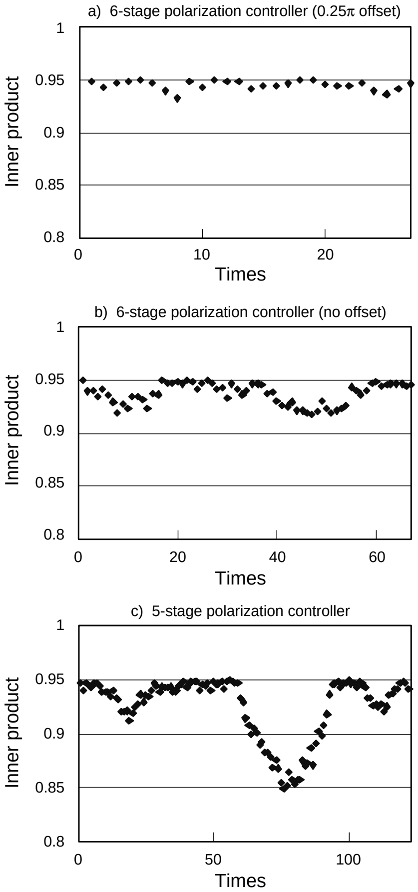


Figure 10 **Results of simulation (inner product < 0.95).**

for three types of polarization controller--6-stage with offset, 6-stage with no offset, and 5-stage.

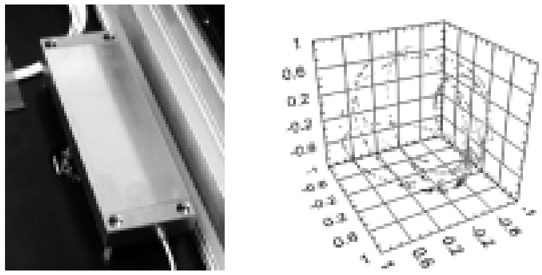
The number of points at which the inner product was 0.95 or less clearly decreases, in the order of 5-stage, 6-stage with no offset, and 6-stage with offset. Also in terms of the minimum value of inner product, there was an increase in the order of 5-stage, 6-stage with no offset and 6-stage with offset. Thus it was confirmed that the 6-stage polarization controller with offset offered the greatest stability.

5. PROTOTYPE POLARIZATION CONTROLLER

A prototype polarization controller actually using VFRs was produced as shown in Figure 11. The VFRs had phase shifting range with angles of rotation (in Stokes space) of approximately $\pi/4\sim9\pi/4$, forming a 6-stage polarization controller with offset.

The results of measurements of output polarized light were obtained using a polarimeter, with a current of 0~100 mA applied to each VFR (other VFRs at 0 mA). The fact that the circular trajectories from the various VFRs do not intersect orthogonally is due to an offset being applied.

Low values were realized for insertion loss (1.37 dB) and PDL (0.04 dB), and it was possible to reduce the size to 90×30×9.5 mm.



a) Visual appearance

b) Results of measurement of output polarization

Number of VFRs	6
Insertion loss	1.37 dB
PDL	0.04 dB
Power consumption	0.6 W per VFR (max)
Response time	<200 µs
Dimensions	90×30×9.5 mm

c) Specifications

Figure 11 **Prototype polarization controller.**

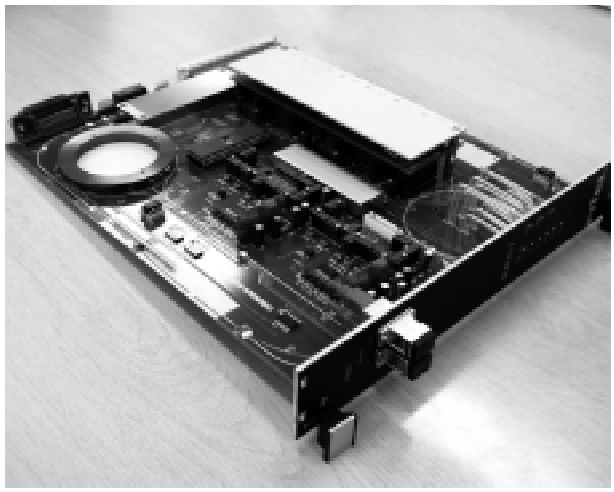


Figure 12 **PMD compensator.**

Currently we are in the process of producing a prototype PMD compensator incorporating the polarization controller described here, and are verifying its operational characteristics (see Figure 12).

6. CONCLUSION

We have developed a polarization controller with an endless tracking function that makes use of variable Faraday rotators (VFRs) having superior optical characteristics and high reliability. At the design stage we introduced rotation group parameters to facilitate discussion of the tracking stability due to the range of phase shifting of the VFRs and the number of VFR stages, and set forth a methodology for achieving a systematic understanding of the conversion structure made by the polarization controller. By this methodology it was also shown that a 6-stage polarization controller with an offset applied to the phase shifting range would in theory operate in a stable manner, and this was confirmed by simulation. A prototype of this polarization controller using actual VFRs was also produced, resulting in a device that is compact and offers good optical characteristics.

It is anticipated that it will be possible through the use of this polarization controller to obtain a PMD compensator that operates in a stable manner.

Further, it is expected that in the next generation of optical transmission systems there will be increasing demand for control of the polarization of signal light, not only in PMD compensators but in non-linear devices, coherent systems and the like. We feel confident that the methodology described here for polarization conversion and the adoption of polarization controllers based on VFRs offers a promising way to solve this kind of polarization problem.

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