Reentrant Fiber Raman Gyroscope

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Abstract—The first experimental demonstration of an active reentrant fiber gyroscope is reported. Raman amplification is used for increasing the number of signal recirculations in the rotation-sensing loop, which improves system sensitivity to rotation rate. A theoretical analysis of the wave mixing between counterpropagating pump and signal fields, interacting through Raman scattering in a polarization-preserving fiber is presented.

I. INTRODUCTION

FIBER-OPTIC rotation sensors have been developed in many different forms. For the passive single-path multiturn Sagnac interferometer approaches [1], the Sagnac phase shift is magnified by using many turns of optical fiber in order to increase the sensitivity of rotation sensing. For the passive resonator approaches [2], the enhancement of Sagnac phase shift is realized by recirculation of a CW optical wave in a relatively short fiber loop. These approaches to fiber gyroscopes have been demonstrated with high rotation sensitivity. In order to achieve wide linear dynamic range with digital rotation output from these gyroscopes, however, nonreciprocal phase shifters (such as frequency shifters [3], [4], high-speed phase modulators [5]), or electronic signal processors [6] are necessary. The performance of the fiber gyroscope is then limited by that of these added components.

The reentrant approach to fiber gyroscopes [7], [8], on the other hand, provides an inherent linear scale factor with frequency readout, as in ring laser gyroscopes. It employs a multiturn fiber coil where a single input pulse injected from an external source recirculates around the fiber loop many times as a fraction of the optical signal is tapped out to be monitored at each turn. As the number of recirculations increases, the Sagnac phase shift induced between the counter-propagating signal pulses is magnified by the number of recirculations. The system output then consists of a pulse train whose envelope is sinusoidally modulated with frequency linearly proportional to the rotation rate, as in the case of a ring laser gyroscope. This approach requires an optical amplifier in the sensing coil that can compensate for the signal loss at each recirculation, in order to obtain a large number of recirculations permitting sensitive rotation measurement.

It is well known that optical amplification in glass optical fibers can be easily achieved through the stimulated Raman scattering (SRS) process [9]. More recently, a large number of signal recirculations (of the order of 10^3) was demonstrated in a fiber delay line using the SRS as an optical amplifier in the fiber circuit [10]. The same technology can be implemented in the active reentrant fiber gyroscope. In this paper, we report the first experimental demonstration of an active reentrant fiber gyroscope with internal Raman gain.

In the theoretical part, Raman scattering involved in the active operation of the reentrant fiber gyroscope is studied. Before describing the principle of the active reentrant fiber gyroscopes, it is necessary to analyze the particular wave-mixing interaction of a pump and a signal electric field propagating in a bidirectional fiber Raman amplifier and in two polarization modes.

First, the specific features of Raman amplification in a polarization-preserving optical fiber with bidirectional pumping are studied with classical Maxwell formalism (Section II-A). It is shown that the pump power attenuation causes the Raman gain distribution along the fiber to be different for the two propagation directions, unless the same amount of pump power is coupled at each fiber end (symmetrical pumping scheme). It is also shown that the Raman gain is maximized when the pump and the signal waves are linearly polarized along either fiber birefringence axis.

In Section II-B, the reentrant fiber Raman gyroscope is analyzed as a fiber system supporting two polarization modes. It is shown that upon rotation of the reentrant fiber loop, the nonreciprocal Sagnac phase shift occurring between the two counterpropagating signal waves causes a sinusoidal modulation of the signal output, the frequency of which is proportional to the rotation rate. In Section III experimental demonstration of the reentrant fiber Raman gyroscope is described. Detailed analysis of optical error sources and the gyroscope performance limit will be in a forthcoming paper.

II. THEORY

A. Raman Gain in Bidirectional Fiber Amplifier

In this section, the evolution of the signal polarization in a birefringent optical fiber having internal Raman gain is analyzed. The Raman gain is assumed to be small so that the parametric or undepleted pump approximation can apply. In order to be relevant to the case of a reentrant fiber gyroscope, the analysis should assume that the pump and the signal waves travel in both directions of the fiber waveguide.
The pump electric field \( \mathbf{E}_p(r, \theta, z, t) \) at frequency \( \omega_p \) providing distributed gain in the optical fiber, as shown in Fig. 1, is assumed to be the superposition of two counterpropagating pump waves \( \mathbf{E}_p^r(r, \theta, z, t) \) and \( \mathbf{E}_p^s(r, \theta, z, t) \). The signal electric field \( \mathbf{E}_s(r, \theta, z, t) \) at frequency \( \omega_s \) is assumed likewise to be the superposition of two counterpropagating signal waves \( \mathbf{E}_s^r(r, \theta, z, t) \) and \( \mathbf{E}_s^s(r, \theta, z, t) \). In the following analysis, it is shown that in the case of bidirectional pumping, Raman gain is caused by simultaneous forward and backward amplification processes, if nonphase-matched terms participating in the interaction are neglected. The results are expressed in terms of gain matrices characterizing the two counterpropagating signal fields. From these results, optimal input conditions for the pump and the signal fields can be derived, and reciprocity properties of the fiber amplifier analyzed.

The following notations are chosen for the field expressions:

1. Fiber slow and fast birefringence axis,
2. Fiber length,
3. Pump and signal propagation constants,
4. Pump and signal field amplitudes,
5. Pump and signal transverse mode envelopes,

with

- \( x, y \) fiber slow and fast birefringence axis,
- \( L \) fiber length,
- \( \beta_p^l, \beta_s^l \) pump and signal propagation constants,
- \( A_i, B_i \) pump and signal field amplitudes,
- \( \psi_j(r, \theta) \) pump and signal transverse mode envelopes,
- \( N_j(j = p, s) \) normalization factors [11]

with

\[
N_j = \left( \frac{c n_j}{8 \pi} \int \psi_j^2(r, \theta) r dr d\theta \right)^{1/2}
\]

\( n_j(j = p, s) \) refractive index at frequency \( \omega_j \).

The pump and signal optical powers are equal to \( P_p = |A_p|^2 + |A_s|^2, P_s = |A_p|^2 + |A_s|^2 \) and \( P_s^r = |B_p|^2 + |B_s|^2 \).

In the plane-wave approximation, Maxwell equations reduce for the signal field \( \mathbf{E}_s \) to

\[
\frac{\partial^2 \mathbf{E}_s}{\partial z^2} - \frac{n_s^2 \partial^2 \mathbf{E}_s}{c^2 \partial t^2} = \mu_0 \frac{\partial^2 P_{NL}(\omega_s)}{\partial t^2}.
\]

\( P_{NL}(\omega_s) \) is the nonlinear polarization oscillating at frequency \( \omega_s \). In the approximation where polarized Raman scattering dominates and using the real fields \( \left( \mathbf{E}_s + \mathbf{E}_s^* \right)/2 \) \( (j = p, s) \), the nonlinear polarization takes the form [11], [12]:

\[
P_{NL}(\omega_s) = \left( 4 \pi \varepsilon_0 \right) 4 \chi^{(3)} \frac{3}{2} \mathbf{E}_p - \mathbf{E}_s + c.c.
\]

where \( \chi^{(3)} = [\chi^{(3)}]_{1111} \) is the (1111) component of the third-order resonant nonlinear susceptibility characteristic of Raman scattering. The factor 4 in front of \( \chi^{(3)} \) in (6) follows the convention of [11]; the factor 3 comes from degeneracy in field products. Replacing (1)-(4) into (6), and using the slowly varying envelope approximation, the following propagation equations for the forward and the backward signal complex amplitudes \( \mathbf{B}' = \left( B'_i, B'_s \right), \mathbf{B}'' = \left( B''_i, B''_s \right) \) can be obtained (see Appendix):

\[
\frac{d\mathbf{B}'(z)}{dz} = \left( \frac{g_r}{2 A_{ps}} \mathbf{I} - \frac{\alpha_s}{2} \mathbf{I} \right) \mathbf{B}'(z)
\]

\[
\frac{d\mathbf{B}''(z)}{dz} = - \left( \frac{g_r}{2 A_{ps}} \mathbf{I} - \frac{\alpha_s}{2} \mathbf{I} \right) \mathbf{B}''(z).
\]

\( \mathbf{I} \) and \( \mathbf{I} \) are the gain matrices for the forward and the backward travelling signal waves, and \( A_{ps} \) an effective interaction area accounting for mode overlap between the pump and the signal fields. In (7)-(8), the Raman susceptibility \( \chi^{(3)} \) has been expressed in terms of the polarized Raman gain coefficient \( g_r \) [9] through the identity

\[
96 \pi \omega_s \chi^{(3)} / n_p n_s c^2 = - i g_r / 2.
\]

The factor \( -i \) accounts for the fact that in the case of Raman scattering, the third-order nonlinear susceptibility \( \chi^{(3)} \) at resonant is negative and imaginary [13]. The term \( \alpha_i / 2 \) where \( \mathbf{I} \) is the identity matrix and \( \alpha_i / 2 \) the signal field attenuation coefficient has been introduced in order to account for propagation loss. It is assumed that the Raman gain coefficient is independent of the relative propagation directions of the pump and the signal waves, which is accepted as being a good approximation [14].

As seen in the Appendix, the coefficients of matrix \( \mathbf{I} \) and \( \mathbf{I} \) contain terms having various phase mismatches (equations (A2)-(A4) and (A10)-(A12)), generated by the different field sources in the development in field products (A1) of \( \mathbf{P}_{NL}(\omega_s) \). For the forward travelling signal wave, the first two terms in this development correspond to forward and backward Raman scattering, respectively, which are self phase-matched interactions; the last two terms correspond to interactions coupling the...
counterpropagating pump fields, which are not phase matched processes.

For simplicity, we assume the pump fields $E'_p, E''_p$ to be linearly polarized along directions forming angles $\theta'_p$ and $\pi - \theta'_p$ with respect to the slow axis $\alpha$, as shown in Fig. 1. It is also assumed that the input fields have the same initial phases at $z = 0$ and $z = L$, respectively, which can be arbitrarily chosen zero. In the basis $(\alpha_0, \alpha)$ of the birefringent axis, the pump field amplitudes are $A'(z) = \sqrt{T_{11}(z)} P'_0 (\cos \theta'_p, \sin \theta'_p)$ and $A''(z) = \sqrt{T_{11}(L-z)} P''_0 (-\cos \theta'_p, \sin \theta'_p)$ with $P'_0 = |A'(0)|^2 + |A''(0)|^2$ and $P''_0 = |A''(0)|^2 + |A''(0)|^2$ being the forward and backward input powers, respectively. The factor $T_{11}(x) = \exp(-\alpha_0 x)$, where $\alpha_0$ is the pump power attenuation coefficient, accounts for pump propagation loss.

It can be seen from the Appendix (c.f. (A2)-(A4) and (A10)-(A12)) that suppression of the off-diagonal coefficients of $\Gamma^+(z)$ and $\Gamma^-(z)$ occurs for $\theta'_p = \theta''_p = \theta_p = 0$ or $\pi/2$, which corresponds to the cases where integration of (7)-(8) from $z = 0$ to $z = \pm L$ (or $z = L$ to $z = \pm L$, respectively, yields:

$$B'(z) = \sqrt{T_{11}(z)} \begin{pmatrix} \sqrt{G^+(z)} & 0 \\ 0 & 1 \end{pmatrix} \cdot B'(0)$$

$$\approx \hat{K}^+(z) B'(0)$$

$$B''(z) = \sqrt{T_{11}(L-z)} \begin{pmatrix} \sqrt{G^-(z)} & 0 \\ 0 & 1 \end{pmatrix} \cdot B''(L)$$

$$\approx \hat{K}^-(z) B''(L)$$

where $T_{11}(x) = \exp(-\alpha_0 x)$ is the signal fiber transmission. The matrices $\hat{K}^\pm$ define the net Raman gains in the two polarization modes, and $G^\pm$ are the Raman gain factors defined by:

$$G^+(z) = \exp \left( \gamma L_f(z) U^+(z) - \frac{2\gamma \sqrt{T_{11}(L)} P'_0 P''_0}{P'^{(\text{tot})}} \sin \left( \frac{\beta_p^+(z)}{\beta_p} \right) \cos \left( \beta_p^+(L-z) \right) \right)$$

$$G^-(z) = \exp \left( \gamma L_f(z) U^-(z) - \frac{2\gamma \sqrt{T_{11}(L)} P'_0 P''_0}{P'^{(\text{tot})}} \sin \left( \frac{\beta_p^-(L-z)}{\beta_p} \right) \cos \left( \beta_p^-(L-z) \right) \right)$$

with $P'^{(\text{tot})} = P'_0 + P''_0$ being the total input pump power,
asymmetry is converted into a nonreciprocal phase shift between the two signal waves, which in the reentrant gyroscope application results in a rotation rate error. In order to suppress this effect, the symmetrical pumping scheme must be employed, for which the integrated gain along the fiber is symmetric, or independent of the signal propagation direction (11)–(12) show that in this case $G^+(z) = G^-(L-z)$.

**Raman Gain Maximization:** The input signal field $E_1^i$ is assumed to be linearly polarized along a direction forming an angle $\theta_1^i$ with respect to the $x_0$ birefringence axis (see Fig. 1). The input signal power being $P_0^i$, the input signal field amplitude is then $B_1^i(0) = \sqrt{P_0^i} (\cos \theta_1^i, \sin \theta_1^i)$. From (9), the forward signal power gain with the pump polarized along the $ox$ axis can be written as:

$$G(\theta_1^i) = T_s \{ 1 + \cos^2 \theta_1^i(G - 1) \}$$

with $T_s(L)$ and $G = G^+(L)$, which takes the same form as in [15]. Then, the power gain is maximized for $\theta_1^i = 0$, i.e., $G_{\text{max}} = G(0) = T_s G$, which corresponds to the case where the input signal is linearly polarized in the direction parallel to the pump. In this case the signal polarization is maintained along the whole fiber length, which in addition to gain maximization represents the most advantageous configuration for the reciprocity properties which are required in fiber gyroscope applications.

**B. Reentrant Fiber Raman Gyroscope**

The reentrant fiber gyroscope is made from a strand of fiber closed upon itself with two directional fiber couplers, as shown in Fig. 3. The different portions of such a fiber system can be described advantageously through the scattering matrix formalism [17].

The first coupler ($C_1$) is used as a beamsplitter for the input signal $E_1^i$, and as a combiner for the waves reflected from the system (in the following, it is referred to as the BS/C coupler). The input signal is an optical pulse with duration $\Delta T$ shorter than the reentrant loop transit time $T_{\text{loop}}$. The two optical pulses generated by the signal splitting in the first coupler propagate along short fiber paths ($F_1$ and $F_2$), respectively, and are coupled in opposite propagation directions into the reentrant loop, forming the sensing coil, through the second fiber coupler ($C_2$). After having circulated along the loop ($F_1$), a fraction of the two counterpropagating pulses is tapped by the coupler ($C_2$) and returns to the coupler ($C_1$). The remaining fraction is coupled again into the loop and recirculates around it. As a result, the reflected signal $E_1^{\text{out}}$ returning to the same fiber end as the input signal is a train of optical pulses with the time separation $T_{\text{loop}}$ (if one neglects the transit times in the short leads $F_1$ and $F_2$). Each of these pulses with electric field component $E_1^{\text{out},(n)}$ corresponds to the recombination of the pair of counterpropagating signal pulses having recirculated $n$ times through the sensing loop.

Following notations similar to that of [17], as applied to the geometry of the reentrant fiber gyroscope, we obtain, with $n$ being the number of signal recirculations ($n \geq 1$):

$$E_1^{\text{out},(n)} = \hat{R}_n E_1^i$$

where $\hat{R}_n$ is the scattering matrix of the system operated in reflection

$$\hat{R}_n = \frac{1}{2} \left( \hat{M}_n e^{i \phi} + \hat{M}_n e^{-i \phi} \right)$$

where $2\phi$ is the nonreciprocal Sagnac phase shift due to the rotation of the gyroscope and

$$\hat{M}_n = \hat{C}_1 \hat{F}_1 \hat{C}_2 \hat{F}_3 \hat{C}_2 \hat{F}_1 \hat{C}_1$$

$$= \hat{C}_1 \hat{F}_1 \hat{C}_2 \hat{F}_3 \hat{C}_2 \hat{F}_1 \hat{C}_1$$

$$= \hat{C}_1 \hat{F}_1 \hat{C}_2 \hat{F}_3 \hat{C}_2 \hat{F}_1 \hat{C}_1$$

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$$= \hat{C}_1 \hat{F}_1 \hat{C}_2 \hat{F}_3 \hat{C}_2 \hat{F}_1 \hat{C}_1$$

with the reentrant loop scattering matrices defined by $\hat{L} = \hat{C}_2 \hat{F}_3$ and $\hat{L} = \hat{F}_1 \hat{C}_1$.

The arrows $\rightarrow$ on the scattering matrices in (15)–(17) indicate which propagation direction is followed by the light through the corresponding optical elements or portions of the fiber system. The coupling matrices $\hat{C}_1 \hat{F}_1$ and $\hat{C}_1 \hat{F}_1$ correspond to straight-through propagation and cross-coupling in the fiber coupler $j = 1$ or 2, respectively.

We consider the case of an ideal, uniform and polarization-maintaining fiber, isolated from magnetic fields...
and having time-independent characteristics. Under such assumptions, the nonreciprocal parts of $\tilde{C}_y$ and $\tilde{C}_s$ vanish [17], and:

$$\tilde{C}_y = \tilde{C}_s' = \tilde{C}_y = \sqrt{(1 - \epsilon)(1 - \eta)} e^{i\pi/4} J$$

$$\tilde{C}_s = \tilde{C}_s' = \tilde{C}_y = \sqrt{(1 - \epsilon)(1 - \eta)} e^{-i\pi/4} J$$

where $\epsilon$ and $\eta$ are the fractional propagation loss and the power coupling ratio of fiber coupler $j = 1, 2$, respectively.

Assuming that the fiber leads corresponding to scattering matrices $F_1$ and $F_2$ have lengths $L_1$ and $L_2$, respectively, and negligible propagation loss, we have likewise $\tilde{F}_1 = \tilde{F}_s = \tilde{F}_y = J(L_1)$, with $J$ being the signal Jones matrix defined in (A5). Finally, using the results of Section II-A, and assuming the pump wave to be linearly polarized along the $\alpha$ birefringence axis, we have $\tilde{F}_3 = \tilde{F}_s = \tilde{F}_y = \sqrt{\tilde{J}} T(L_1) K$ with $K = K^+(L_1) = K^-(0)$. Using (19), the reentrant loop scattering matrix $\tilde{L}$ writes:

$$\tilde{L} = \tilde{L} = \tilde{L} = \begin{pmatrix} \sqrt{\Delta} \exp \left( i \beta_1^* L - \frac{\pi}{4} \right) & 0 \\ 0 & \sqrt{\Delta} \exp \left( i \beta_1^* L - \frac{\pi}{4} \right) \end{pmatrix}$$

with $\Delta = \gamma_{12} \eta_{12} T_1 G$, $\Delta_s = \gamma_{12} \eta_{12} T_s$, $\gamma_{12} = 1 - \epsilon_2 (\lambda_s)$ and $\eta_{12} = \eta_1 (\lambda_s)$.

Equations (15)-(17) show that the system scattering matrix $\tilde{R}_s$ is a function of $\tilde{L}^s$. Since $\tilde{L}$ is diagonal, $[\tilde{L}^s]_{ij} = \delta_{ij} ([L]_i)^s_i$. It is clear that then from (20) that the signal amplitude along the $\alpha$ birefringence axis vanishes with increasing number of signal recirculations, since $\Delta_s = \gamma_{12} \eta_{12} T_s < 1$. On the other hand, the gain $G$ along the $\alpha$ birefringence axis can be adjusted so that

$$\Delta_s = \gamma_{12} \eta_{12} T_s G = 1$$

(21)

which expresses that the internal gain in the fiber loop compensates exactly for the overall loop loss. As a result of the fulfillment of condition (21), the modulus of $[\tilde{L}]_{11}$ is independent of $n$, i.e., the amplitudes of the signal pulses are maintained constant at each recirculation.

The critical pump power $P_{\text{crit}}$ for which (21) is verified is, using (11) for $z = L$ and neglecting the interference term in $\sin (\beta_2^* L)/\beta_2^*$.

$$P_{\text{crit}} = \frac{A_{\gamma_{12} T_s}^2}{\gamma_{12} T_s} \frac{1 - T_{\eta_{12} \gamma_{12} T_s}}{1 - \eta_{12}} \gamma_{12} T_s \gamma_{12} T_s$$

(22)

with $T_{\eta_{12}} = T_{\eta_{12}} (L)$ and $L_{\eta_{12}} = L_{\eta_{12}} (L)$. The factor $1 - T_{\eta_{12}} \gamma_{12} T_s$ in (22) comes from the infinite number of pump power recirculations in the reentrant fiber loop [18], which occurs when $\eta_{12} \neq 0$. Equation (22) shows that the critical pump power $P_{\text{crit}}$ is independent of the coupling ratio $\eta_{12}$ of the BS/C coupler, and decreases as the passive reentrant loop transmission $\gamma_{12} \eta_{12} T_s$ increases. Minimization of $P_{\text{crit}}$ is obtained for $\eta_{12} = 0$ and $\eta_{12} = 1$, which requires the reentrant loop coupler to have a strong multiplexing effect [10], [19].

A convenient way to calculate the output signal power is to use the signal coherency matrix [20], which can be written, with the notations adopted in this paper as:

$$S_{\text{out}} = \frac{N_2^2}{N_1^2} \begin{pmatrix} \langle E_i^{\text{out}} E_i^{\text{out}} \rangle & \langle E_i^{\text{out}} E_j^{\text{out}} \rangle \\ \langle E_i^{\text{out}} E_j^{\text{out}} \rangle & \langle E_i^{\text{out}} E_j^{\text{out}} \rangle \end{pmatrix}$$

(23)

where the brackets $\langle \cdot \rangle$ signify time average over many cycles of optical waves. As shown in (23), the average signal power is given by the trace of the coherency matrix.

Given the input signal coherency matrix $S_{\text{in}}$, and a fiber system characterized by a scattering matrix $T$, the output signal coherency matrix is given by $S_{\text{out}} = T S_{\text{in}} T^\dagger$, where $\dagger$ stands for the Hermitian conjugate.

Using (14)-(20), the system scattering matrix $\tilde{R}_s$ takes the form

$$\tilde{R}_s = \sqrt{A_{\gamma_{12} T_s} (1 - \eta_{12})} \cos (n \phi_i)$$

(24)

$$\begin{pmatrix} \langle \Delta_s \rangle^{-n/2} \exp (i \phi_i^* ) & 0 \\ 0 & \langle \Delta_s \rangle^{-n/2} \exp (i \phi_i^* ) \end{pmatrix}$$

with $\phi_i = \beta_i^* (L_1 + L_2 + n L) - (n - 3) \pi / 4$, $A = \gamma_{12} T_s (1 - \eta_{12})^2 / \eta_{12}$, $\eta_{12} = \eta_1 (\lambda_s)$, and $\gamma_{12} = 1 - \epsilon_2 (\lambda_s)$. Using (14), (23), and (24) the output signal coherency matrix $S_{\text{out}}$, corresponding to $n$ signal recirculations in the loop, is

$$S_{\text{out}} = \tilde{R}_s S_{\text{in}} \tilde{R}_s^* = A P_{\text{crit}} \eta_{12} (1 - \eta_{12}) \cos^2 (n \phi_i)$$

$$\times \begin{pmatrix} \langle \Delta_s \rangle^{-n/2} \sin 2 \theta_i \exp (-i n \Delta \beta, L) & \langle \Delta_s \rangle^{-n/2} \sin 2 \theta_i \exp (i n \Delta \beta, L) \\ \langle \Delta_s \rangle^{-n/2} \sin 2 \theta_i \exp (i n \Delta \beta, L) & \langle \Delta_s \rangle^{-n/2} \sin 2 \theta_i \exp (-i n \Delta \beta, L) \end{pmatrix}$$

(25)
with $P_{in}^s$ being the peak power of the input signal pulse, $\theta_i$ being the angle of the linear polarization of the input signal with respect to the $\alpha$ birefringence axis, and with the approximation $L_1 + L_2 \ll nL$.

The final general expression for the peak power $P_{out, (n)}$ in the $n$th pulse of the output signal train of a reentrant fiber gyro, using polarization maintaining fiber with the pump polarization along one of the characteristic birefringent axes of the fiber, and with signal polarization at $\theta_i$ to the pump polarization, is given by the trace of (25), and is as follows:

$$P_{out, (n)} = Tr(\mathcal{S}^{out}) = BP_{in}^s \cos^2 \theta_i \left[ 1 + \frac{\tan^2 \theta_i}{G^\alpha} \right] \left( \gamma_{s2} \gamma_{s2} (1 - \eta_s) (1 - \eta_r) \eta_{s1} / \eta_{s2} \right) G^\alpha \cdot e^{-n_{sl}L} \left( \frac{1 + \cos 2n\phi_s}{2} \right).$$

Here $B = \gamma_{s1} \gamma_{s2} (1 - \eta_s) (1 - \eta_r) \eta_{s1} / \eta_{s2}$, and $\eta_s$ and $\eta_r$ represent, respectively, the power transmission and coupling ratios of the two couplers, $i = 1, 2$: $G$ is the Raman gain for loop length $L$ (see (13)), $\alpha_r$ is the fiber loss coefficient at the signal wavelength, and $2\phi_s$ is the Sagnac phase shift.

It is clear from (26) and the definition of $B$ that output signal power maximization is achieved by choosing $\eta_{s2} = 0.5$, which corresponds to a 50-percent splitting efficiency in the BS/C coupler. In addition, this condition also minimizes the nonreciprocal phase shift due to the optical Kerr effect which results from the difference in optical powers between the two counterpropagating signal pulses. Another output signal power maximization can be realized by choosing $\theta_i = 0$, or the input signal polarization parallel to the pump polarization (which is along the $\alpha$ birefringence axis in our example). As seen in Section II-A, this condition maximizes the Raman gain in the reentrant fiber loop. Finally, the coefficient $B$ in (26) can be made large by choosing a value close to unity for the loop coupling ratio $\eta_{s2}$, except $\eta_{s2} = 1$ for which no input signal is coupled into the loop. In addition, a high loop coupling ratio minimizes the overall loop loss and consequently, minimizes the critical pump power $P_{p, cr}^s$, as shown in (22). Under such optimal conditions, the output signal power becomes

$$P_{out, (n)} = \frac{A}{4} (\Delta_s) \left( \frac{1 + \cos (2n\phi_s)}{2} \right) P_{in}^s. \tag{27}$$

Equation (27) shows that the envelope of the output signal pulse train power is modulated by two factors. First, the nonreciprocal Sagnac phase shift $2n\phi_s$, increasing proportionally to the number of signal recirculations, results in a sinusoidal power modulation of the output signal. Second, the effect of signal recirculations in the active reentrant loop causes an exponential power modulation, which is a growing or a decaying function of the recirculations, depending on the loop transmission or net gain $\Delta_s$. When the internal Raman gain exactly compensates for the overall loop loss, i.e., $\Delta_s = 1$, the output pulse train envelope is a raised cosine waveform. The frequency of this sinusoidal modulation is then, through the nonreciprocal Sagnac phase shift, a function of the rotation rate.

Expressing the Sagnac phase shift $2\phi_s$ as a function of the rotation rate $\Omega$, we have [21]:

$$2\phi_s = 2\pi \frac{LD\Omega}{c \lambda_s} = 2\pi FT_{loop} \tag{28}$$

where

$$F = \frac{2\pi}{n_s^2 \lambda_s} \tag{29}$$

is the frequency of the envelope modulation, $T_{loop} = n_s L / c$ the loop transit time, $n_s^2$ the signal refractive index along the $\alpha$ birefringence axis and $D$ the loop diameter. Using (27) and (28) with $\Delta_s = 1$, the output signal power becomes:

$$P_{out, (n)} = \frac{1 + \cos (2\pi F \cdot nT_{loop}) A}{4} P_{in}^s. \tag{30}$$

As seen in (29)-(30), the characteristic feature of the reentrant fiber gyrooscope is that the modulation frequency $F$ of the signal output scales linearly with the rotation rate $\Omega$, as in the case of the ring laser gyroscope [21]. For detecting small rotation rates, long optical delays ($nT_{loop}$) must be achieved, corresponding to large numbers of signal recirculations. As seen in (26) and (27), passive operation of the reentrant fiber gyrooscope does not permit such long optical delays, since the output signal power decays rapidly as $(\Delta_s)^2$, the loop transmission $\Delta_s$ being in this case lower than unity. On the other hand, active operation of the system cancels the effect of the signal attenuation, and increases indefinitely the optical delay as long as the pump is turned on. Actually, the maximum optical delay achievable is determined by the decay of output signal-to-noise ratio, which is caused by the amplification of the spontaneous noise, or stimulated scattering.

III. EXPERIMENT

A reentrant fiber Raman gyroscope was implemented experimentally. The fiber used for the sensing loop was not a polarization holding fiber. Although different from the ideal case of a polarization maintaining device described in the theoretical part, a Sagnac interferometer made from a non-polarization-preserving sensing loop can exhibit the identical reciprocity properties provided adequate polarization control is achieved upon recombination of the signal waves [21].

A. Experimental Setup

The setup used in the experiment is pictured in Fig. 4. The pump wave at $\lambda_p = 1.064 \mu m$ is provided by the
TEM$_{00}$ output of a polarized Nd:YAG laser operating in the CW regime. An acoustooptic cell synchronized with the signal pulses modulates the pump output to form square pulses with arbitrary durations. A Glan polarizer and a quarter-wave plate ensure partial optical isolation of the pump source from power returning from the fiber system. The pump wave is coupled through the nonreciprocal port of the fiber gyroscope with a 20× microscope objective. An index-matching oil drop is placed between the coupling objective and the fiber end to prevent Fresnel reflection and consequently to reduce feedback to the pump source (not shown in the figure). A fiber polarization controller [22] is placed at the pump input end in order to optimize the input pump wave polarization; since about half of the pump power is reflected by the system towards this input pump end, such polarization control associated with the optical isolator makes possible to minimize the consequent feedback effect onto the pump source.

The signal at the Raman-shifted wavelength of $\lambda_s = 1.12\,\mu m$ is generated by a fiber Raman laser. This laser source is an auxiliary 1200-m-long single-mode fiber coil which is pumped by a Q-switched Nd:YAG laser (300-ns pulsewidth, 1-kW peak power) operating at $\lambda_p = 1.064\,\mu m$ at the repetition rate of 100 Hz (a silicon photodetector, placed in a beam reflection, generates a signal which ensures synchronization of the acoustooptic cell modulating the other pump source output). The output Stokes pulses at $\lambda_s = 1.12\,\mu m$, generated in the auxiliary fiber coil by amplification of spontaneous scattering, are filtered by a grating, and coupled after passing through a polarizer (not shown in the figure) into the reciprocal port of the fiber gyroscope by a 20× microscope objective. The fiber input end acting also as a spatial filter, and the coupled signal linewidth $\Delta\lambda_s$ can be reduced from the spectrally large Stokes input to about 2 nm. Depending on the coupling efficiency, the coupled signal peak power can be varied up to about 300 mW in that linewidth. The input signal polarization is optimized through a fiber polarization controller placed at the fiber input end. It was observed that the signal was dependent on the polarization state of the pump. This has been attributed to the existence of a small polarization dependence of the sensing loop fiber coupler, which affects the pump coupling efficiency in the loop, as well as the signal overall loop loss. In addition, a certain amount of stress-induced birefringence in the non-polarization preserving fiber loop is also responsible for a slight dependence of the Raman gain on the input polarization conditions.

In order to be able to monitor the reflected signal coming from the system, a directional fiber coupler [23] with a 50-percent splitting efficiency is placed at the signal input port. It is well known [21] that this reflected output consists of the two counterpropagating signal waves that had traveled the reciprocal optical paths. At the other fiber end of the system, the nonreciprocal signal output is monitored from the portion of the signal wave which is reflected by the Glan polarizer placed in front of the nonreciprocal port. The reentrant Sagnac interferometer, described in detail in Section II-B, is assembled from discrete elements by using capillary-bonded splices with about 0.2-dB insertion loss.

The reentrant loop is made from a strand of fiber closed upon itself by a directional fiber coupler. The two free ends of the reentrant fiber loop coupler are spliced to the two output ends of a second fiber coupler which acts as a beam splitter/combiner (BS/C) for both pump and signal waves. The nonpolarization-preserving fiber used for the reentrant loop is 1200-m-long, with attenuation coefficients $\alpha_p = 1.3\,\text{dB/km}$, $\alpha_s = 1\,\text{dB/km}$; it has a 5.2 μm effective core diameter and a cutoff wavelength of $\lambda_c = 1.064\,\mu m$. From these parameters and (A8), the theoretical effective mode overlap area is $A_{pp} = 13.2\,\mu m^2$, using a Gaussian approximation for the mode envelopes. The fiber couplers used in the experiment are of the mechanically polished type [23], with an insertion loss of the order of a few percents ($\gamma_1 \approx \gamma_2 \approx 0.95$). With the exception of the reentrant loop coupler, the fiber couplers...
used in the setup were fabricated with a 25-cm curvature radius, for which the multiplexing effect between the pump and the signal waves is small ($\eta_{p1} = \eta_{s1} = 0.5$). The reentrant loop fiber coupler was fabricated with a long curvature radius of 4 m which, due to the increase of the interaction length, enhances the effect of multiplexing [19]. With such a fiber coupler, there exists a tuning position for which the pump coupling ratio is zero ($\eta_{p2} = 0$) and the signal coupling ratio maximized ($\eta_{s2} = 0.73$ in the experiment). As a result, all the pump power is coupled into the fiber loop, which maximizes the Raman gain, while the signal loop loss is minimized. In addition, as pointed out in previous work [10], a zero pump coupling ratio prevents the pump wave from recirculating in the loop and interfering with itself, which otherwise would result in gain fluctuations due to pump phase noise [24].

Using a standard coupler for the reentrant fiber loop, for which the pump power could recirculate in the loop, it was observed that the resulting pump interferences, caused fast pump polarization fluctuations, resulting in a nonreciprocal polarization scrambling of the recirculating output signal. The use of a multiplexer coupler with zero pump coupling ratio for the reentrant loop is then justified not only for consideration of Raman gain stability, but also as a condition for reciprocal operation of the system.

Both reciprocal and nonreciprocal signal outputs are analyzed by germanium photodetectors after passing through interference filters having a peak transmission at $\lambda = 1.13 \mu m$. The amplified outputs of the photodetectors are then monitored with a storage oscilloscope. Polarization matching of the two reflected signal waves is achieved by using fiber polarization controllers placed in the reentrant fiber loop (C2–F3–C2 in Fig. 4) and in the intermediate loop (C1–F1–C2–F2). The first polarization controller is set to minimize the output corresponding to the first signal pulse which is reflected by the system and received at the nonreciprocal port. This first pulse is the recombination of the two signal pulses which have been rejected by the reentrant loop coupler (C2) and have circulated only in the intermediate loop. By tuning the BS/C coupler (C1) to a coupling ratio value of 0.5, and by matching the signal polarizations through the intermediate loop polarization controller, the first pulse from the nonreciprocal port can be zeroed. The zero output at this port is explained by the fact that, in this transit along the intermediate loop, one of the signal waves (CCW in the figure) has achieved two crosstalkings through the BS/C coupler, while the other signal wave (CW in the figure) has achieved two straight-through crossings in this coupler. As a result there exists a relative phase shift $\Delta \phi_{NR}$ between the two waves which, due to the $\pi/2$ phase shift associated with wave coupling in the directional coupler, corresponds to a half cycle (i.e., $\Delta \phi_{NR} = \pi$). The same zeroing of the nonreciprocal port output is then achieved for the following signal pulses which have recirculated in the reentrant fiber loop, by using the reentrant fiber loop polarization controller. This operation actually consists in making the CW and CCW optical paths reciprocal around the reentrant fiber loop. In order to achieve a good reciprocity, it is necessary to insert a polarizer at the common input/output port. In this experiment, however, this polarizer was not included, and an approximate reciprocity was achieved using polarization controllers.

### B. Operation of the Reentrant Gyroscope in the Passive and the Active Modes

When no pump power is coupled into the system, a signal pulse train is obtained at the reciprocal port whose envelope decays exponentially with the optical delay. The input signal power has then to be maximized in order to obtain the largest possible number of recirculations at the system output. Fig. 5 shows oscilloscope traces of the output signals obtained at the reciprocal (R) and nonreciprocal (NR) ports. With the system at rest ($\Omega = 0$) and the polarization matching optimized, the NR port output is zero, whereas the R port output shows the expected decaying pulse train (Fig. 5(a)). In the latter, the intensities of the two first pulses are above the detector saturation level; away from this saturation regime, the intensity ratio of two consecutive pulses corresponds to an overall loop loss of about 3 dB, as seen in the figure. Due to this relatively fast decay, only 7 signal recirculations are obtained in the passive mode.

In presence of rotation (Fig. 5(b)), the R output shows that a sinusoidal modulation of the signal envelope occurs. Due to the power decay, only two periods of the rotation-induced modulation are visible in this output. From (29), (30) with a loop diameter of $D = 18$ cm and a measured 54-kHz modulation frequency, the rotation rate is evaluated to be $0.49 \text{ rad/s}$, in agreement with the estimated applied rotation. As seen in the figure, the NR port output shows also a decaying pulse train with sinusoidal modulation, which is delayed by a half cycle with respect to the R port output, as predicted by the theory. In this passive mode of operation, the number of signal recirculations being relatively small, the dynamic range of the reentrant gyroscope is severely limited.

In the active mode, a square pump pulse of arbitrary duration is coupled through the NR port of the system (see Figs. 3 and 4). The leading edge of the pump pulse is synchronized with the signal-generating Raman laser (see Fig. 4) so that it is advanced by about 6 $\mu s$ with respect to the input signal pulse; by the time the signal pulse is coupled into the fiber gyroscope R port, the pump pulse occupies the whole reentrant fiber loop, which guarantees gain reciprocity. With the aforementioned system parameters, an unpolarized Raman gain coefficient $g_r = 6.9 \times 10^{-14} \text{ m/W}$ evaluated from [15], and using (22), the calculated critical pump power for which the loop loss is compensated by the Raman gain is $P_{p, cr} = 135 \text{ mW}$. In order to ensure an undepleted pump regime, the recirculating signal power has to be decreased to a level at least one order of magnitude below the pump power level. With a loop coupling ratio $\eta_{s2} = 0.73$, the maximum input sig
nal for linear amplification regime is then evaluated to be 50 mW.

Fig. 6 shows oscilloscope traces of the signals at \( \lambda = 1.12 \mu m \) detected at the R and the NR output ports, when a 190-\( \mu s \)-long pump pulse having the required critical power is coupled into the system. When the system is at rest (Fig. 6(a)), the R port output is made of a pulse train with constant amplitude, as long as the pump is on. The depression of the envelope level which is visible in the figure is due to pump power fluctuations about the critical value. When the pump is turned off (end of the pulse train of the R output in Fig. 6(a)), a fast decay of the recirculating pulses occurs, causing the signal to vanish. The NR port output shown in the same figure has a square pulse background which is due to a certain amount of back-scattered pump power through the interference filter. In this NR output, small residual output pulses can be observed, showing that, in the active mode of operation, the polarization control is not as efficient as it is in the passive mode. This was attributed to a modulation of the signal polarization by the pump, since the pump and signal waves will experience different birefringence in the fiber. Then, when the pump is coupled into the fiber loop, the two output signal polarizations are changed, which requires a polarization matching readjustment. Other possible sources of this nonreciprocity include a) the unequal pump power splitting in the two propagation directions (asymmetrical pumping), and b) the occurrence of pump power fluctuations, of the order of the loop transit time induced by optical feedback. Both of these effects result in a nonreciprocal optical Kerr effect induced phase shift.

When rotation of the sensing loop occurs, the output signal pulse train at the R port shows a sinusoidal modulation, as seen in Fig. 6(b) and (c). The same impulse response, shifted by a half cycle is visible at the NR port.

The modulation frequencies corresponding to the two cases are 12.9 kHz and 24.4 kHz, which with the system parameters correspond to rotation rates of 0.11 and 0.22 rad/s, in good agreement with the estimated applied rotations. The R port outputs show that, in the presence of rotation and Raman amplification in the loop, a fairly large amplitude modulation of the signal pulse envelope can be observed, which is actually limited by the polarization control of the system. As such, this experiment constitutes the first demonstration of an active fiber gyroscope, where the Sagnac effect is magnified by achieving many lossless signal recirculations in the sensing loop, through Raman amplification. Because of pump power fluctuations induced by optical feedback into the pump source caused by the reflection by the system, sizeable Raman gain fluctuations causing output envelope instability limited the achievable numbers of recirculations to small amounts. More efficient optical isolation of the pump source, utilizing for instance an optical isolator along with an electronic feedback control on the pump intensity, should make it possible in future work to achieve the very large number of signal recirculations already demonstrated with the active recirculating delay line [10]. In such conditions, several orders of magnitude in rotation rate sensitivity should be gained.
IV. Conclusion

The first experimental demonstration of an active, reentrant fiber gyroscope is reported. In this alternative to rotation sensing which uses pulsed signals, the nonreciprocal phase shift induced by the Sagnac effect is magnified by having two signal waves recirculating many times in the sensing loop. Direct optical amplification by Raman scattering has been implemented as a means to compensate for the loop loss and thus to maximize the number of signal recirculations. The reentrant gyroscope has been realized in an all-fiber nonpolarization-maintaining version utilizing fiber-optic components. A multiplexing fiber coupler was used for the reentrant loop in order to suppress the effect of pump phase noise and consequent gain and polarization fluctuations in the loop. Due to a sizeable amount of residual optical feedback into the pump source causing Raman gain fluctuations, the active operation of the system was limited to short durations, allowing only the detection of relatively large rotation rates.

A theoretical analysis of the active reentrant Raman gyroscope, which involves bidirectional Raman scattering has been presented. It has been shown that ideally, the system should be polarization-preserving, with both the pump and the signal propagating in the same polarization modes.

In future work, orders of magnitude in rotation rate sensitivity should be gained by achieving a necessary Raman gain stabilization over long optical delays, which involves adequate control of the pump source intensity, as well as optical isolation from the fiber system. Nonreciprocity due to polarization wandering should be suppressed by using a polarization-maintaining device and a polarizer at the common input/output port. Finally, very large numbers of signal recirculations could be achieved by using short optical pulses at a wavelength where the fiber dispersion is minimized. The use of optical solitons [25] for the signal for which self optical Kerr effect compensates for fiber dispersion might prove in the future to be an attractive alternative.

Like the ring laser and the passive resonator gyroscopes, the reentrant fiber Raman gyroscope has a built-in linear scale factor with frequency readout. The specific features, advantages, and potential performance of the reentrant fiber Raman gyroscope makes it suitable for applications in fundamental physics, for instance geophysics and cosmology.

APPENDIX

Derivation of the Signal Fields Propagation Equations

Using (1)-(3), the nonlinear polarization \( P_{NL}(\omega_s) \) in (6) becomes, for the forward travelling signal wave:

\[
P_{NL}(\omega_s) = 4\pi \varepsilon_0 (4\chi^{(3)}_N) \frac{1}{2} E_p(E^*_p \cdot E'_s)
\]

\[
= 24\pi \varepsilon_0 (4\chi^{(3)}_N) \left\{ E'_p(E^*_p \cdot E'_s) + E^*_p(E^*_p \cdot E'_s) \right\}
\]

\[
= 24\pi \varepsilon_0 (4\chi^{(3)}_N) \frac{\psi^2_p \psi^2_s}{N_p N_s} e^{-i\omega_s t} \tilde{f}(z) \hat{\Gamma}^+(z) B^*(z)
\]  

(A1)

with \( B^* = (B'_s, B'_p) \) being the signal complex amplitude, and \( \tilde{f}(z) \) being a matrix with the following coefficients:

\[
\tilde{f}(z) = \begin{pmatrix}
|A'_s|^2 + |A'_p|^2 & A'_s A'_p e^{2i\beta_0(z-L/2)} \\
A'_s A'_p e^{-2i\beta_0(z-L/2)} & |A'_p|^2 + |A'_s|^2
\end{pmatrix}
\]

(A2)

\[
\tilde{f}(z) = A'_s A'_p e^{i(\Delta\beta_0 + \Delta\beta_L)} + A'_s A'_p e^{i(\Delta\beta_L + \Delta\beta_0)}
\]

(A3)

\[
\tilde{f}(z) = A'_s A'_p e^{i(\Delta\beta_0 - \Delta\beta_L)} + A'_s A'_p e^{i(\Delta\beta_0 + \Delta\beta_L)}
\]

(A4)

Replacing expression (3) of the signal field in propagation equation (5), and using the slowly varying approximation \( d^2 B^*_l/dz^2 \ll 2\beta^*_l dB^*_l/dz \), one obtains the following vector equation:

\[
\psi_s = \frac{1}{2\varepsilon_0 c n_s} \psi_i \left( \begin{pmatrix} e^{i\beta_0 z} & 0 \\ 0 & e^{i\beta_0 z} \end{pmatrix} \right)
\]

(A5)

Multiplying both sides of (A6) by \( \psi_i \), using (A1) and integrating over the fiber cross-sectional area \( \Sigma \), it is found

\[
\frac{dB^*(z)}{dz} = i \frac{96\pi^2 \omega_s \chi^{(3)}_N}{n_p n_s c^2 A_{gs}} \hat{\Gamma}^+(z) B^*(z)
\]

(A7)

where \( A_{gs} \) is a mode overlap area defined by [11]:

\[
A_{gs} = \int \int \int \psi^2_s(r, \theta, \phi) r d\phi d\theta \cdot \int \int \int \psi^2_s(r, \theta, \phi) r d\phi d\theta
\]

(A8)

The same procedure as used in the forward signal case, but using the backward travelling signal field \( E^*_b(r, \theta, z, t) \) as defined in (4) leads to the propagation equation for the backward signal complex amplitude

\[
\frac{dB^*(z)}{dz} = -i \frac{96\pi^2 \omega_s \chi^{(3)}_N}{n_p n_s c^2 A_{gs}} \hat{\Gamma}^-(z) B^*(z)
\]

(A9)
with $\hat{F}(z)$ defined by

$$\hat{F}_{11}(z) = \hat{A}_{11}^*(z)$$

$$\hat{F}_{22}(z) = A_{22}^* e^{-i(\Delta z + \Delta L)}$$

$$+ A_{12}^* A_{21}^* e^{i(\Delta z - \Delta L)} + A_{11}^* A_{22}^* e^{i(\Delta z L - \Delta L)}$$

$$+ A_{12}^* A_{11}^* e^{i(\Delta z L - \Delta L)} = \hat{F}_{22}(z)$$

$$\hat{F}_{12}(z) = \hat{F}_{21}(z).$$

(A11)

(A12)

References


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K. Fesler, photograph and biography not available at time of publication.

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