Polarization Analysis of Brillouin Scattering in a Circularly Birefringent Fiber Ring Resonator

Alain Küng, Luc Thévenaz, and Philippe A. Robert

***Abstract*—A complete analysis of the eigenstate of polarization (ESOP's) in a Brillouin fiber ring laser using fibers with a high circular birefringence is proposed in this paper. Conditions to obtain circular ESOP's for application in a Brillouin fiber optic current sensor are highlighted as well as conditions to have stable ESOP's for applications in other passive or active sensors. Measurements are performed on a Brillouin laser using a mechanically twisted fiber ring resonator confirming the theoretical predictions. Ring resonator configurations using linearly birefringent fibers are compared to configurations using circularly birefringent fibers.**

***Index Terms*—Brillouin scattering, optical fiber birefringence, optical fiber devices, optical fiber lasers, optical fiber polarization, optical resonators, optical scattering.**

I. Introduction

BRILLOUIN fiber ring lasers have already found many applications such as Brillouin fiber-optic gyroscopes [1], microwave phase-modulated generators [2], narrow linewidth laser sources [3], fiber frequency shifters [4], and current sensors [5]. Brillouin fiber ring lasers can show excellent performances such as submiliwatt threshold [6] and conversion efficiency over 50% [7]. But prediction of these characteristics is highly dependent on the Brillouin gain along the fiber ring resonator. Since the Brillouin gain depends on the relative polarizations of the pump and of the Stokes wave, it is of prime importance to analyze the eigenstates of polarization (ESOP) for the pump and the Stokes wave along the fiber ring resonator to determine the overall Brillouin gain after one round-trip. This analysis has been performed for several ring configurations using fibers with a high linear birefringence [8] or single polarization fibers [9]. Some of these configurations using rotated splices at 90° show stable ESOP's, so that prediction of their characteristics is accurate and in addition immune to thermal fluctuations.

The first part of this paper summarizes the characteristics of these ring resonators using linear birefringence fibers in terms of ESOP's, thermal stability and Brillouin gain. In the second part of this paper a complete theoretical analysis of the ESOP's in a Brillouin fiber ring laser using fibers with a highly circular birefringence is proposed, showing that comparable performances can be obtained. Conditions to have circular ESOP's are specially addressed for applications in Brillouin fiber optic current sensors [5] or to have stable ESOP's for applications in other passive or active sensors as reported in [10]. Then for the first time to our knowledge, measurements performed on a Brillouin ring laser using a twisted single-mode fiber confirm the theoretical predictions. Finally a discussion compares the merit and demerit of using a circularly birefringent or linearly birefringent fiber in a ring resonator.

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II. Linearly Birefringent Fiber Ring Resonators

A maximum gain in Brillouin fiber ring lasers is obtained when the ESOP's of the pump are kept parallel to those of the Stokes wave. This can be done using all polarization maintaining fiber ring resonators [11], but since the birefringence is subject to change with the temperature, a small crosstalk between the ESOP's results in non-negligible interferometric noise [12], [13]. Several papers proposed to suppress one ESOP using either polarizing fibers [14] or an anisotropic coupler [9], but the ESOP's orthogonality is removed and their differential round-trip loss must be at least of 10 dB [9]. The best way is to make the ESOP's immune to variation of the birefringence by introducing in the ring a rotational splice at 90° with respect to the fiber axis [15], [16]. The adjacent resonances are thus always separated by a π phase shift and will never coincide in the frequency domain. The ESOP's are kept at 45° to the fiber axis and change from linear to circular, back to linear and so on along the fiber resonator [8]. Therefore the polarization state at the input and output of the ring changes while the temperature drifts. For optimum pumping the pump polarization must continuously match one of the ring's ESOP's. Moreover the Brillouin gain is not maximum, but equally split over the two ESOP's. Taking this into account a recently proposed configuration uses two rotating splices at 90° dividing the ring in two equal length. The ESOP's are linear corresponding to the fiber axes and the Brillouin gain is maximum. The separation between adjacent ESOP's as well as their immunity to birefringence changes only depends on the residual difference in the birefringence between the two parts of the ring. This configuration is therefore also sensitive to nonuniformity of temperature changes over the fiber ring.

Any fiber ring resonator is subject to the following physical limitation: the central frequency of the Brillouin gain curve increases for growing temperature whereas the resonance frequency of any kind of fiber ring simultaneously decreases, so that any Brillouin fiber ring laser operates without mode hopping only in a definite temperature range [17].

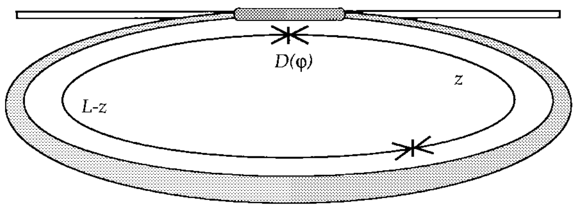

Fig. 1. Schematic description of the fiber ring resonator. L is the total ring length, z is the distance from the coupler to the observation point and $D(\varphi)$ is the adjusted linear birefringence nearby the coupler.

III. Theoretical Analysis of a Circularly Birefringent Fiber Ring Resonator

The analysis of the ESOP's for circularly birefringent fiber ring resonator will demonstrate that they have characteristics equivalent to linearly birefringent fiber ring resonators together with unique specific features: the circular birefringence preserves the shape of the polarization while propagating along the fiber. This unique feature is essential for fiber optic current sensors [5].

The analysis refers to a fiber ring resonator as shown in Fig. 1 following the same method presented in [16]. The resonator is assumed to be made of a circularly birefringent fiber and of an ideal coupler with no birefringence. In addition let assume that the linear birefringence can be adjusted nearby the coupler.

For the pump wave, the one round-trip transmission matrix observed at point z $(0<z<L)$ is given by

$$T_{\text{pump}} = \sqrt{(1-\kappa)(1-\gamma)}\exp(-\alpha L) M|_0^z D(\varphi) M|_z^L \quad (1)$$

where

$$M|_{z1}^{z2} = e^{i\beta(z2-z1)} \cdot \begin{bmatrix} \cos(\Delta\beta(z2-z1)) & \sin(-\Delta\beta(z2-z1)) \\ \sin(\Delta\beta(z2-z1)) & \cos(-\Delta\beta(z2-z1)) \end{bmatrix} \quad (2)$$

with

$$\Delta\beta = (\beta_L - \beta_R)/2 \quad \text{and} \quad \beta = (\beta_L + \beta_R)/2 \quad (3)$$

and

$$D(\varphi) = \begin{bmatrix} 1 & 0 \\ 0 & e^{i\varphi} \end{bmatrix} \quad (4)$$

and where κ is the coupling coefficient of the coupler, γ the coupler loss, α the fiber loss, L the length of the ring resonator, β_L and β_R the propagation constant for each circular polarization, and φ the phase retardance of the linear birefringence nearby the coupler.

The eigenvalues of the ESOP's are

$$\begin{aligned} \lambda_{P1} = \tfrac{1}{2}\sqrt{(1-\kappa)(1-\gamma)}\exp(-(\alpha+i\beta)L) \\ \times [(e^{i\varphi}+1)\cos(\Delta\beta L) \\ + \sqrt{(e^{i\varphi}+1)^2\cos^2(\Delta\beta L) - 4e^{i\varphi}}] \quad (5) \\ \lambda_{P2} = \tfrac{1}{2}\sqrt{(1-\kappa)(1-\gamma)}\exp(-(\alpha+i\beta)L) \\ \times [(e^{i\varphi}+1)\cos(\Delta\beta L) \\ - \sqrt{(e^{i\varphi}+1)^2\cos^2(\Delta\beta L) - 4e^{i\varphi}}]. \quad (6) \end{aligned}$$

These eigenvalues correspond to two orthogonal eigenvectors E_{P1} and E_{P2} which have elliptic polarizations except for two definite values of the linear birefringence φ.

1) For $\varphi = m2\pi$, where m is an integer, the eigenvalues are

$$\begin{aligned} \lambda_{P1} &= \sqrt{(1-\kappa)(1-\gamma)}\exp(-(\alpha+i(\beta-\Delta\beta))L) \\ &= \sqrt{(1-\kappa)(1-\gamma)}\exp(-(\alpha+i\beta_R)L) \quad (7) \\ \lambda_{P2} &= \sqrt{(1-\kappa)(1-\gamma)}\exp(-(\alpha+i(\beta+\Delta\beta))L) \\ &= \sqrt{(1-\kappa)(1-\gamma)}\exp(-(\alpha+i\beta_L)L) \quad (8) \end{aligned}$$

and the associated eigenvectors are circular

$$E_{P1} = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ -i \end{bmatrix} \quad (9)$$

$$E_{P2} = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ i \end{bmatrix}. \quad (10)$$

2) For $\varphi = \pi + m2\pi$ where m is an integer, the eigenvalues are

$$\lambda_{P1} = \sqrt{(1-\kappa)(1-\gamma)}\exp(-(\alpha+i\beta)L) \quad (11)$$

$$\lambda_{P2} = -\sqrt{(1-\kappa)(1-\gamma)}\exp(-(\alpha+i\beta)L) \quad (12)$$

and the associate eigenvectors are linear

$$E_{P1} = \begin{bmatrix} \sin(\Delta\beta(L/2-z)) \\ -\cos(\Delta\beta(L/2-z)) \end{bmatrix} \quad (13)$$

$$E_{P2} = \begin{bmatrix} \cos(\Delta\beta(L/2-z)) \\ \sin(\Delta\beta(L/2-z)) \end{bmatrix}. \quad (14)$$

Under this latter condition the eigenvalues are related by

$$\lambda_{P2} = \lambda_{P1}e^{i\pi}. \quad (15)$$

This means that the phase difference between adjacent resonances is fixed to π independently of the change in the circular birefringence due to temperature fluctuations, as shown in [10].

The ESOP's of the Stokes wave traveling in the counter-clockwise direction can be deduced from the ESOP's of the pump. In the same reference frame, the CCW transmission matrix is the complex conjugate of the transposed CW matrix, but since the Stokes wave experiences a Brillouin gain and has a slightly different frequency, a gain term G is included and the propagation constants β_L and β_R are replaced by the propagation constants β_{BL} and β_{BR} at the Brillouin frequency

$$T_{\text{Stokes}} = G T_{\text{pump}}^{t^*}(\beta_{BL}, \beta_{BR}) \quad (16)$$

where G is the Jones matrix of the total Brillouin gain integrated over one round-trip in the fiber ring. As this gain is polarization dependent but usually small in a Brillouin fiber ring laser, the eigenvalues of the Stokes ESOP's are in a first order approximation the complex conjugate of the pump ESOP's, where the propagation constants are replaced by the propagation constants taken at the Brillouin frequency. The two ESOP's are under this approximation mutually orthogonal

$$E_{B1} = E_{P1}^*(\beta_{BL}, \beta_{BR}) \quad (17)$$

$$E_{B2} = E_{P2}^*(\beta_{BL}, \beta_{BR}) \quad (18)$$

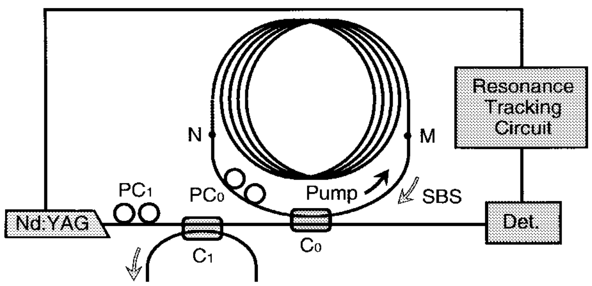

Fig. 2. Set-up of the Brillouin fiber ring laser using a circularly birefringent fiber ring resonator.

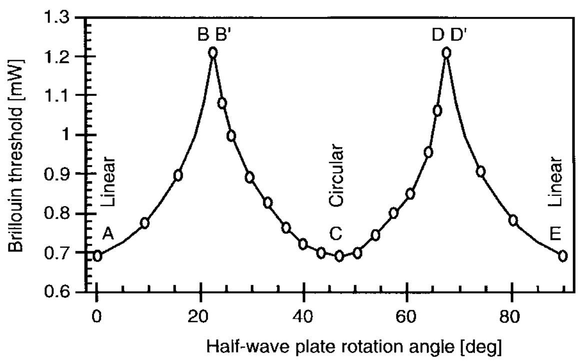

Fig. 3. Variation of the Brillouin threshold due to variation of the ESOP's gain over one round-trip by rotating the half-wave plate of PC_0.

and the eigenvalues of the Stokes ESOP's are equal to the complex conjugate of the eigenvalues of the pump ESOP's, but at the Brillouin frequency and multiplied by a Brillouin gain which is different for each Stokes ESOP

$$\lambda_{B1} = \exp(g_1 L)\lambda_{P1}^*(\beta_{BL}/\beta_{BR}) \tag{19}$$
$$\lambda_{B2} = \exp(g_2 L)\lambda_{P2}^*(\beta_{BL}/\beta_{BR}). \tag{20}$$

The determination of the Brillouin linear gain coefficients g_1 and g_2 of each Stokes ESOP is obtained by solving the coupled mode equations for the pump wave and the Stokes wave

$$\frac{dI_P(z)}{dz} = -g_B|(E_{P1}, E_{Bj})|^2 I_P(z) I_{Bj}(z) - 2\alpha I_P(z) \quad (j = 1, 2) \tag{21}$$
$$\frac{dI_{Bj}(z)}{dz} = -g_B|(E_{P1}, E_{Bj})|^2 I_P(z) I_{Bj}(z) + 2\alpha I_{Bj}(z) \quad (j = 1, 2) \tag{22}$$

where g_B is the Brillouin linear gain coefficient when the pump and the Stokes wave have the same polarization, I_P is the intensity of the pump, and I_{B1} and I_{B2} are the light intensities of the Stokes waves corresponding to each ESOP. The inner product between the ESOP of the pump and the ESOP of the Stokes wave represents the fraction of pump power used for exciting each ESOP of the Stokes wave. Assuming the pump and the Stokes wave propagates in opposite directions the result of this inner product will be different for circular and linear polarization states. Since the propagation constants of the pump wave and the Stokes wave to be almost equal, the difference in the overall birefringence after one round-trip experienced by the pump and the Stokes wave is negligible. Thus, the following conclusions can be asserted.

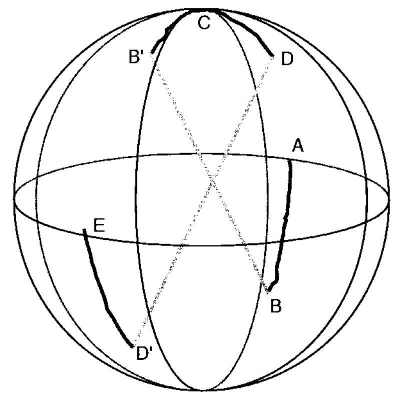

Fig. 4. Behavior of the measured lasing ESOP on the Poincaré sphere when rotating the half-wave plate of PC_0. According to positions on Fig. 3, jumping to the orthogonal ESOP is visible between BB' and DD'.

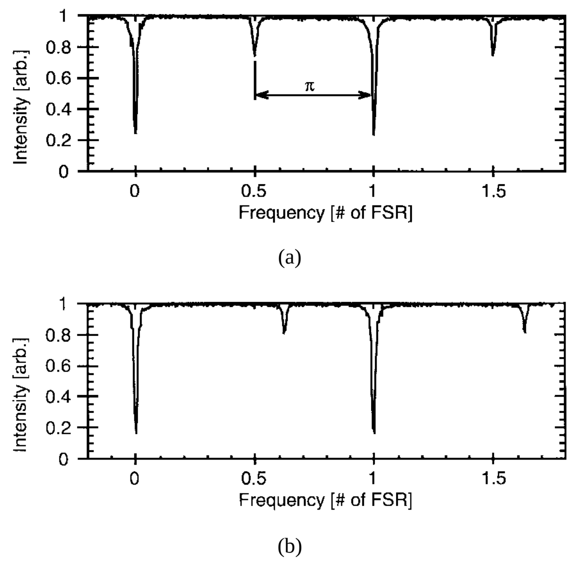

Fig. 5. (a) Adjacent resonances are always separated by π for linear ESOP. (b) Adjacent resonances depend on the circular birefringence for other ESOP's.

1) For $\varphi = m2\pi$, where m is an integer, the ESOP's are circular all along the fiber resonator. The inner product (E_{P1}, E_{B1}) is equal to zero for two polarization corresponding to identical ESOP's hereon propagating in opposite directions, called aligned ESOP's. Whereas the inner product (E_{P1}, E_{B2}) is equal to one for two polarization corresponding to orthogonal ESOP's hereon propagating in opposite directions, called crossed ESOP's. The Stokes wave experiences maximum gain and the Brillouin laser emission occurs in the crossed polarization with respect to the pump.
2) For $\varphi = \pi + m2\pi$ where m is an integer, the ESOP's are linear and rotating along the fiber resonator, and the inner product is equal to one for two aligned ESOP's

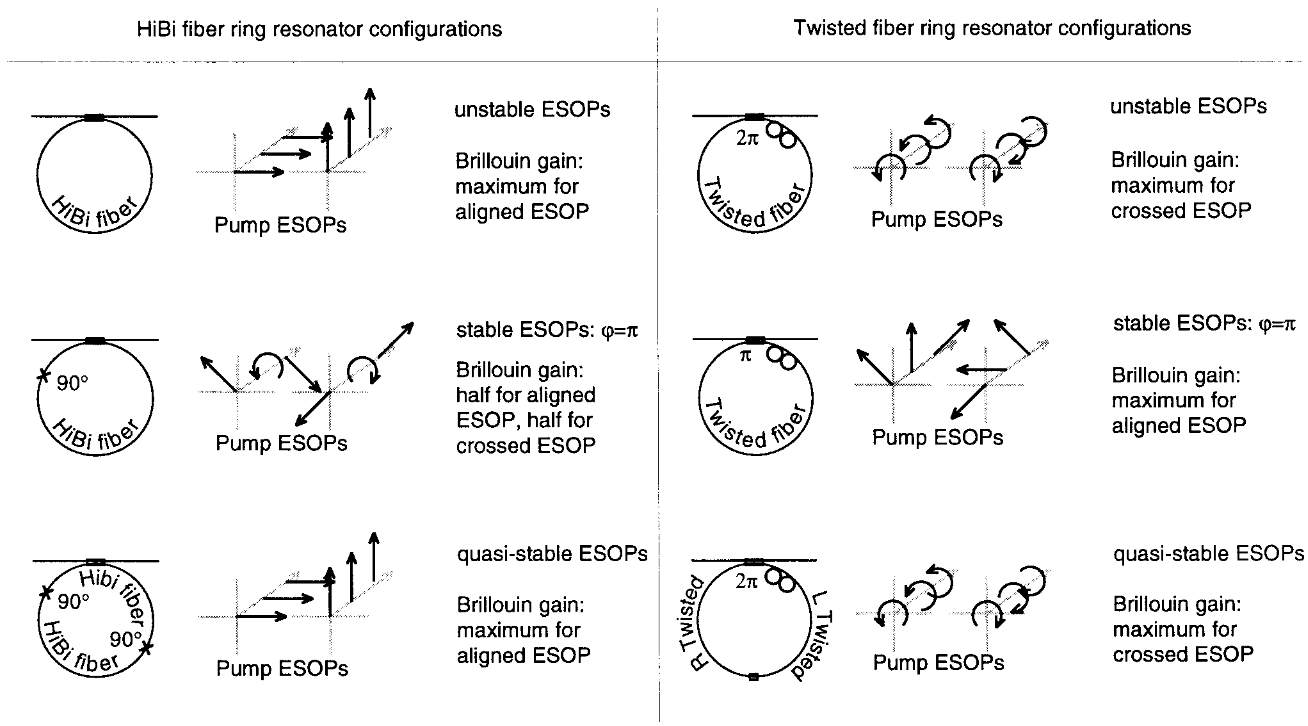

Fig. 6. Comparison of fiber ring resonators using HiBi fibers and using twisted fibers in terms of ESOP and Brillouin gain.

(E_{P1}, E_{B1}) and equal to zero for two crossed ESOP's (E_{P1}, E_{B2}). The Stokes wave also experiences maximum gain but the Brillouin laser emission occurs in the same polarization as the pump. The resonant frequencies of two orthogonal ESOP's are separated by a half resonator resonance spacing.

3) For all other values of φ the ESOP's are kept with the same ellipticity all along the fiber ring resonator. The Brillouin gain is then unequally split over the two ESOP's and the Brillouin laser emission occurs in the ESOP showing the highest gain.

IV. Measurements on a Circularly Birefringent Fiber Ring Resonator

In order to confirm the results of the theoretical analysis, a Brillouin fiber ring laser using circularly birefringent fiber as shown in Fig. 2 was achieved. Two parts can be distinguished in the fiber resonator separated in Fig. 2 by points M and N. The fiber coil part is made of standard single mode fiber mechanically twisted at 20 turns/m. The obtained circular birefringence exhibits a beat length of about 0.5 m and the overall residual linear birefringence in the coil is less than 15°. The coupler part is made of a 5/95% coupler C_0 followed by a polarization controller PC_0 in order to make the total linear birefringence between points M and N tunable.

The free spectral range FSR, the Finesse F, and the length L of the passive resonator are, respectively, FSR $= 9.52$ MHz, $F = 64$, and $L = 21.5$ m. The polarization of the Nd : YAG pump laser is set to match one ESOP of the resonator through the polarization controller PC_1 and its frequency is kept in resonance with the fiber ring by using a FM sideband technique [18]. Finally the backward Brillouin emission is collected by the coupler C_1. Let notice here that the Brillouin gain frequency width of about 35 MHz is much larger than one FSR, so that gain discrimination between adjacent ESOP's can be neglected and the gain variation is considered to be only due to the polarization matching.

Once the polarization controller PC_0 is properly set to get a minimum Brillouin threshold, the resonator eigenstates are either linear or circular and the half-wave plate rotation results in a continuous change of the linear birefringence in the coupler part. Variations of the measured Brillouin threshold are plotted in Fig. 3. As theoretically predicted, minimum threshold is obtained for the same ESOP's when the polarization is purely linear (positions A and E) and also for the crossed ESOP's when the polarization is purely circular (position C). Rotating the half-wave plate changes the ratio of the Brillouin gain experienced by each ESOP. At positions B and D each ESOP have exactly equal gain and at these positions the Brillouin emission jumps to its orthogonal ESOP. This corresponds to a change in the Brillouin frequency shift and the polarization jumps to the antipode on the Poincaré sphere. This is clearly observed for measurements shown in Fig. 4.

As predicted by the theory, if the ESOP's are linear (positions A and E), the phase separation between adjacent resonances is fixed to π, leading to a fixed frequency difference of a half FSR as shown in Fig. 5(a). For all other ESOP's this frequency difference depends on the ring circular birefringence as shown in Fig. 5(b). This enables discrimination between linear ESOP's and circular ESOP's.

Discrimination can also be done by observing the sensitivity of the Brillouin fiber ring laser to the Faraday effect. It is known that the Faraday effect induces a nonreciprocal phase shift for circularly polarized light only. Using this property in a gyroscopic configuration as in [5], a Brillouin fiber optic current sensor will show maximum sensitivity at position C and no sensitivity at positions A or E.

Accurate determination of the Brillouin gain g_B of the fiber can be made using the expression [7] for the threshold intensity when the pump frequency is kept in resonance with the fiber ring and its polarization matches one of its ESOP's

$$I_{\mathrm{th}} = \frac{-\ln(\kappa\kappa_r)}{gL}\frac{(1-\sqrt{(\kappa\kappa_r)})^2}{(1-\gamma)(1-\kappa)} \tag{23}$$

where κ_r is the overall round-trip loss and g the effective Brillouin linear gain. At position B or D, each ESOP have equal gain and $g = g_B/2$ is in excellent agreement with measurements performed using a direct gain measurement method [19]. At position A, E, or C, the Brillouin gain is maximum, but not exactly equal to g_B because the shape of the ESOP's is maintained only in the coil part of the resonator. Thus, the gain in the coupler part is not maximized and cannot be neglected.

V. Discussion

The results of the theoretical analysis were confirmed by measurements performed on a Brillouin fiber ring laser using a mechanically twisted fiber. Spun HiBi fibers [20] could be used instead of twisted fibers but they exhibit a circular birefringence only at a definite temperature.

The analysis showed that thermal stability of the ESOP's is obtained only when having linear ESOP's. Therefore a novel ring configuration can be proposed using left-handed together with right-handed twisted fiber to obtain circular and stable ESOP's as needed for Brillouin current sensors. Fig. 6 summarizes all ring configurations discussed in this paper in terms of ESOP and Brillouin gain.

The following remarks should emphasize the specificity of the two types of fibers. HiBi fibers and especially couplers made out of them are expensive. They exhibit a beat length of about 1 mm to be compared with the 0.5 m beat length for twisted fibers, making their birefringence about 500 times more sensitive to temperature changes. But this makes them much more immune to polarization crosstalk than twisted fibers. Performing a low-loss splice with less than 1° error on the axis alignment is not an easy task. On the other hand polarization controllers that must be included in twisted fiber ring resonators are sensitive to temperature changes. Therefore UV induced birefringence could be an interesting solution [21].

VI. Conclusion

The proposed analysis of the ESOP's in a Brillouin fiber ring laser using fibers with circular birefringence highlights the conditions required for having circular or linear ESOP's. When the ESOP's are circular as needed for application in Brillouin fiber optic current sensors the Brillouin threshold is minimum, but the ESOP's are sensitive to thermal fluctuations. When the ESOP's are linear the Brillouin threshold is also minimum and in addition the ESOP's are immune to thermal fluctuations. Measurements performed on a Brillouin fiber ring laser using a mechanically twisted fiber are in excellent agreement with the predicted behavior. The final discussion comparing different fiber ring resonators configurations using HiBi fibers to configurations using twisted fibers clearly shows their respective specificity.

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From 1968 to 1974, he was with Les Câbleries et Tréfileries de Cossonay where his research interests lay in new products and new manufacturing processes, including optical fibers. From 1974 to 1979, he has been engaged in the development and installation of the first optical cables made in Switzerland. Since 1979, he has been a Professor at the EPFL and Head of the Laboratory of Metrology. His current research activities concern guided optics, optical fibers, and integrated optics with applications in optical signal processing, sensors, and telecommunications.