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Raman amplification with reduced polarization impairments in the fibre with tailored spin profile

Research Article

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Abstract: By using two-section fibre where the first section has no spin and the second one is periodically spun, we demonstrate reduced polarization dependent gain and polarization mode dispersion (0.3 dB and 0.0072 ps·km$^{-1/2}$ correspondently) in a distributed fibre Raman amplifier.

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Keywords: polarization mode dispersion • spun fibre • fibre Raman amplifier

1. Introduction

Strong demand in increasing bandwidth, distance, and bit rate of signal transmission for broadcasting media and medical applications has renewed the attention to optical fibres with the PMD reduced by fibre spinning [1, 2]. Application of broadband fibre Raman amplifiers (FRAs) in optical telecom links appears as the next natural step to reduce the transmission system cost, increase the amplification bandwidth, and extend the link span [3]. However, further application of distributed Raman amplification in such fibres with the most customary periodic spin leads to deteriorated performance of the optical link caused by increased gain dependence on the pump and signal SOPs, *i.e.* polarization dependent gain (PDG) [3–9]. Thus, to enable high-speed and long-distance transmission of broadband optical signals, one needs to find a solution that employs a Raman amplifier with minimum dependence on the pump and signal polarizations, while simultaneously keeping the suppressed PMD. At a first glance, these seem as mutually excluding requirements if the realization is attempted in the same fibre. However, Sergeyev *et al.* have recently showed that it is possible to meet these requirements based on application of two-section fibre where the first section has no spin and the second one is periodically spun [7]. As a result, it has been shown that PDG and PMD can be suppressed to the 0.13 dB and 0.032 ps·km$^{-1/2}$ correspondently [7]. To suppress PMD

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further down to 0.0072 ps·km$^{-1/2}$, we report herein an approach to optimize parameters for the first section of fibre, namely the correlation length and PMD.

2. Model of two-section fibre Raman amplifier with reduced polarization impairments

The recently derived vector model of a fibre amplifier describes the evolution of pump and signal waves in terms of vectors $\mathbf{s} = (s_1, s_2, s_3)$ and $\mathbf{p} = (p_1, p_2, p_3)$ pointing to positions on the Poincaré sphere [7, 8]. Due to the Raman process, the signal wave is amplified and the pump wave is depleted, while due to the birefringence both of them are rotating around the birefringence axis $\mathbf{w}$ [7, 8]. It is known from experimental measurements that the PDG for backward pumping is significantly lower than for forward pumping, while the average gain is higher [4, 6]. Hence, to consider more instructive and practical example, here we deal with the forward pumping. Next, we choose the reference frame in Stokes space such a way that X-axis coincides with the birefringence axis at the input of fibre. In view of the results obtained by R. H. Stolen for Raman amplification in polarization maintaining fibre [3], there exist two pump SOPs for which the PDG take the maximum and minimum value. The first SOP is (1,0,0) and the second one is any which provide equal sharing of the pump power between two orthogonal eigenstates, for example (0,0,1). In our previous publications and we have found, both experimentally [6] and theoretically [7, 8], that because SM fibre can be characterized in terms of averaged value of birefringence strength, it preserves properties of PM fibre including two SOPs for the maximum and minimum PDGs. In Ref. [8] we have demonstrated for fibres without spin that the signal and pump SOPs rotate on the Poincaré sphere in the same direction but at different rates b_s and b_p around the local birefringence axis ($b_i = \pi/L_{bi}$ is the birefringence strength, L_{bi} is the beat length) [8]. If the difference $b_p - b_s$ is much higher than de-correlation rate L_c^{-1}, then $\mathbf{s}$ and $\mathbf{p}$ vectors reach mutually parallel and orthogonal orientations and oscillatory behaviour occurs for the averaged projection of signal SOP on the pump SOP, *i.e.*, for $\langle x \rangle = \langle \mathbf{s} \cdot \mathbf{p} \rangle$. As a result, the projections corresponding to the max/min Raman gain, *i.e.*, $\langle x_{max} \rangle$ and $\langle x_{min} \rangle$, oscillate in anti-phase along the fibre and merge at distances of $z_n = nT/2$, where T is the spatial period, and n is integer [8]. As follows from the results of Refs. [7] and [8], the PDG (in units of dB) depends on projections $\langle x_{max} \rangle$ and $\langle x_{min} \rangle$ as follows

$$\begin{aligned} \mathrm{PDG} &= 10 \log \left(\frac{s_{0\,\max}}{s_{0\,\min}} \right) \\ &= 10 \log \left(\frac{1 + \frac{gP_{in}}{2} \int_0^L \exp\left(-\alpha_p z\right) \langle x_{\max} \rangle \, dz}{1 + \frac{gP_{in}}{2} \int_0^L \exp\left(-\alpha_p z\right) \langle x_{\min} \rangle \, dz} \right), \end{aligned} \quad (1)$$

where L is the fiber length, g is the Raman gain coefficient, P_{in} is the input pump power, and α_p describes losses at the pump wavelength. Thus, if we combine the short-length fibre ($L_1 = z_1$) with the long periodically spun fibre, one can mitigate PDG and PMD simultaneously. For this case, projections $\langle x_{max} \rangle$ and $\langle x_{min} \rangle$ are the same at the input of the periodically spun fibre, and do not contribute to the PDG over the length of this fibre for a wide range of spinning amplitudes. Therefore, maximum and minimum PDG can be calculated from the following expressions which are valid for the fibre without spin [7, 8]

$$\begin{aligned} \mathrm{PDG}^{\max} &= \frac{10\varepsilon_1 \left(1 + 2\varepsilon_3^2\right)}{\ln(10) \left(\varepsilon_2 \left(\varepsilon_2 + 1/2\right) + \varepsilon_3^2\right)}, \\ \mathrm{PDG}^{\min} &= \frac{20\varepsilon_1 \varepsilon_3}{\ln(10) \left(\varepsilon_2 \left(\varepsilon_2 + 1/2\right) + \varepsilon_3^2\right)}. \end{aligned} \quad (2)$$

Here $\varepsilon_1 = gP_{in}L_c/2$, $\varepsilon_2 = \alpha_s L_c$, $\varepsilon_3 = \pi \; D_p^{(1)} c (2L_c)^{1/2} (1/\lambda_p - 1/\lambda_s)$, λ_p and λ_s are the pump and signal wavelengths, $D_p^{(1)}$ is the PMD parameter of the first section of fibre, L_c is the correlation length, α_s is the signal losses. The minimum length of the short-length fibre L_1 can be found as follows [7, 8]

$$L_1 = 2\pi L_c \Big/ \sqrt{4\varepsilon_3^2 - 1/4}. \quad (3)$$

It is well known that spin induced reduction factor (SIRF) for the periodic spin profile $A = A_0 \sin(f_0 z)$ (A_0 and f_0 are spin amplitude and frequency) can reach the minimum value of less than 0.01 for the phase-matching condition $A_0 \approx 1.2$ [1, 2]. Therefore for this case, the differential group delay (DGD) for a long-length periodically spun fibre is much less than DGD for a short section of fibre without spin. Thus, SIRF for PMD in the case of two-section fibre can found as [7]

$$SIRF \Big|_{A_0 \to 1.2} \approx \sqrt{\left[(L_c/L) \left(\exp\left(-L_1/L_c\right) - 1 \right) + L_1/L \right]}. \quad (4)$$

We find that the minimum PMD value in the two-section fibre $D_{p,min}$ and parameters L_c, L_1, $D_p^{(1)}$ for the first section can be found from Eqs. (3) and (4) based on the following expressions:

$$D_{p,\min} = \frac{\sqrt{4\pi - 1}}{4\pi c\sqrt{L}\left(1/\lambda_p - 1/\lambda_s\right)},$$
$$\sqrt{L_c}D_p^{(1)} = \frac{1}{4\pi c\left(1/\lambda_p - 1/\lambda_s\right)}, \tag{5}$$
$$L_1 \approx 4\pi L_c.$$

To justify the method of parameter optimization of the first section of fibre to reach the minimum PMD and PDG values, we have used the model of PMD in spun fibres reported in Ref. [2]

$$\frac{d\,SIRF^2}{dz'} = \varepsilon_4\left\langle\hat{\Omega}_1\right\rangle,$$
$$\frac{d\left\langle\hat{\Omega}_1\right\rangle}{dz'} = -\left\langle\hat{\Omega}_1\right\rangle + 2\alpha(z)L_c\left\langle\hat{\Omega}_2\right\rangle + 1,$$
$$\frac{d\left\langle\hat{\Omega}_2\right\rangle}{dz'} = -2\alpha(z)L_c\left\langle\hat{\Omega}_1\right\rangle - \left\langle\hat{\Omega}_2\right\rangle - \varepsilon_5\left\langle\hat{\Omega}_3\right\rangle, \tag{6}$$
$$\frac{d\left\langle\hat{\Omega}_3\right\rangle}{dz'} = \varepsilon_5\left\langle\hat{\Omega}_2\right\rangle,$$

and equations for the PDG accounting for the fibre spin profile, PMD value, and pump SOP reported in Ref. [7]

$$\frac{d\langle s_0\rangle}{dz'} = \varepsilon_1\exp\left(-\varepsilon_2 z'\right)\langle x\rangle,$$
$$\frac{d\langle x\rangle}{dz'} = \varepsilon_1\exp\left(-\varepsilon_2 z'\right)\langle s_0\rangle - \varepsilon_3\langle y\rangle,$$
$$\frac{d\langle y\rangle}{dz'} = \varepsilon_3\left[\langle x\rangle - \tilde{p}_1(0)\ \tilde{s}_1(0)\exp\left(-z'\right)\right] - 2\alpha(z)L_c\langle u\rangle - \frac{\langle y\rangle}{2}, \tag{7}$$
$$\frac{d\langle u\rangle}{dz'} = 2\alpha(z)L_c\langle y\rangle - \frac{\langle u\rangle}{2}.$$

Here $\langle\ldots\rangle$ means averaging over the birefringence fluctuations along the fibre, $\mathbf{s} = s_0\mathbf{s}$, $\hat{s}$ and $\hat{\mathbf{p}}$ are the unit Stokes components for the signal and pump waves ($s_0 = |\mathbf{s}|$ is the length of $\mathbf{s}$), $\langle x\rangle = \langle\tilde{p}_1\tilde{s}_1 + \tilde{p}_2\tilde{s}_2 + \tilde{p}_3\tilde{s}_3\rangle$ is the projection of the signal SOP onto the pump SOP, $\langle y\rangle = \langle\tilde{p}_3\tilde{s}_2 - \tilde{p}_2\tilde{s}_3\rangle$, $\langle u\rangle = \langle\tilde{p}_3\tilde{s}_1 - \tilde{p}_1\tilde{s}_3\rangle$, $\alpha(z) = \partial A(z)/\partial z$ is the spin rate, $\left\langle\hat{\Omega}_i\right\rangle$ (i =1,2,3) are averaged and normalized components of the PMD vector, $\varepsilon_4 = L/L_c$, and $\varepsilon_5 = 2\pi/L_{b,s}$. The length of the PMD vector is equal to the DGD, *i.e.*, $|\mathbf{\Omega}| \equiv \sqrt{\Omega_1^2 + \Omega_2^2 + \Omega_3^2} = \Delta\tau$. The PDG and PMD for the distributed Raman amplifier can be found from Eqs. (6) and (7) as follows [1, 2, 7, 8]:

$$\mathrm{PDG} = 10\log\left[\frac{\left\langle s_0^{\max}(L)\right\rangle}{\left\langle s_0^{\min}(L)\right\rangle}\right], \quad D_p = D_p^{(un)}SIRF, \tag{8}$$

$D_p, D_p^{(un)}$ are the PMD parameter for the fibre with and without spin correspondently, and L is the fibre length [1, 2].

In this paper, we neglected both pump depletion and the signal-induced XPM which is valid when the pump power is much larger than the signal power. Additionally, the pump induced cross-phase modulation (XPM), *i.e.* term $\varepsilon_{sp}\boldsymbol{P}\times\boldsymbol{S}$ has been eliminated by transformation shown in Ref. [9]. As follows from Eq. (7), polarization dependent gain is a function of the length of the signal Stokes vector which is invariant under transformations like mentioned. Thus, NPR caused by pump induced XPM has no affect on polarization dependent gain [9].

3. Results and discussion

Calculations of the minimum PMD value and maximum/minimum PDG for two-section fibre have been done first using Eqs. (2), (5) for the following parameters: L = 10 km, α_s = 0.2 dB/km, λ_p = 1460 nm, λ_s = 1550 nm, g = 1.8 W^{-1}km^{-1}, P = 1 W. As a result we have obtained optimal parameters for the first section of fibre as $D_p^{(1)} = 0.1$ ps·km$^{-1/2}$, L_c = 5 m, $L_1 \approx 62.8$ m and, finally, $D_{p,min} = 0.0072$ ps·km$^{-1/2}$, PDG$^{(max/min)}$ = 0.18 dB/0.1 dB for the parameters of the first section fibre corresponding to the minimum PMD value (Figs. 1-3).

The results of calculations of PMD parameter and PDG with Eqs. (6)-(8) for two-section fibre (without spinning/periodically spun) and one-section periodically spun fibre with the spinning frequency $f_0 = 0.37$ m^{-1} are shown in Figs. 2 and 3. As follows from Fig. 2, the simplified approach considered in previous section (Eqs. (2) and (5)) and advanced model lead to quite close values for PDG in the wide range of spin amplitudes A_0 and for PMD at $A_0 \approx 1.2$. Thus, both approaches demonstrate opportunity to reduce the PDG and PMD to the low values acceptable for high-speed optical communication, namely PDG = 0.3 dB and $D_{p,min} = 0.0072$ ps·km$^{-1/2}$. Unlike this, in one-section periodically spun fibre with the spinning frequency $f_0 = 0.37$ m^{-1} it is possible to reach only PDG = 10 dB for the same PMD of $D_p = 0.0072$ ps·km$^{-1/2}$ (Fig. 3). As follows from Ref. [9], polarization dependent gain PDG$_d$ for the case of depolarized pump with any degree of polarization DOP can be written as PDG$_d$ = DOP PDG$_0$

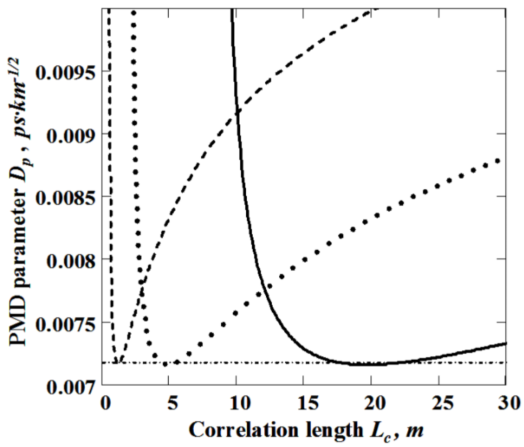

Figure 1. PMD parameter D_p as a function of the correlation length L_c in the two-section fibre according to Eqs. (3), (4). $D_p^{(1)}$ =0.05 ps·km$^{-1/2}$ (solid line), $D_p^{(1)}$ =0.1 ps·km$^{-1/2}$ (dotted line), $D_p^{(1)}$ =0.2 ps·km$^{-1/2}$ (dashed line), minimum of PMD for two-section of fibre (dash-dotted line).

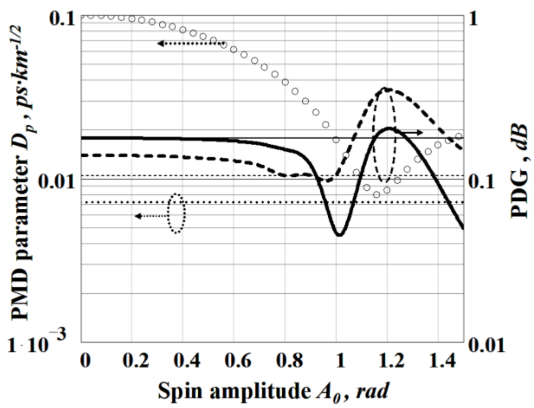

Figure 2. PMD parameter D_p (circles and dots), max/min (solid/dashed line) PDG as a function of the spinning amplitude $A_0$for two-section fibre. Approximate values for PMD from Eq. (4) (dotted line), for maximum and minimum PDG from Eq. (2) (thin solid and dashed lines). Results of modelling for two-section fibre: PMD (circles), maximum/minimum PDG (thick solid/dashed line). Parameters: L = 10 km, α_s = 0.2 dB/km, λ_p = 1460 nm, λ_s = 1550 nm, g = 1.8 W^{-1}km^{-1}, P = 1 W, f_0 = 0.37 m^{-1}, $D_p^{(1)}$ = 0.1 ps·km$^{-1/2}$, L_c = 5 m, f_0 = 0.37 m^{-1}.

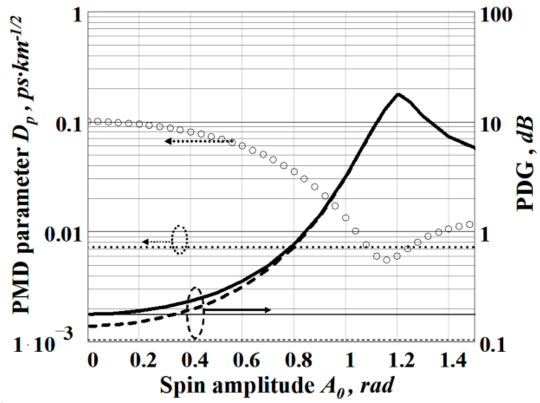

Figure 3. PMD parameter D_p (circles and dots), max/min (solid/dashed line) PDG as a function of the spinning amplitude $A_0$for one-section periodically spun fibre. Approximate values for PMD from Eq. (4) (dotted line), for maximum and minimum PDG from Eq. (2) (thin solid and dashed lines). Results of modelling for two-section fibre: PMD (circles), maximum/minimum PDG (thick solid/dashed line). Parameters: L = 10 km, α_s = 0.2 dB/km, λ_p = 1460 nm, λ_s = 1550 nm, g = 1.8 W^{-1}km^{-1}, P = 1 W, f_0 = 0.37 m^{-1}, $D_p^{(1)}$ = 0.1 ps·km$^{-1/2}$, f_0 = 0.37 m^{-1}·, L_c = 5 m.

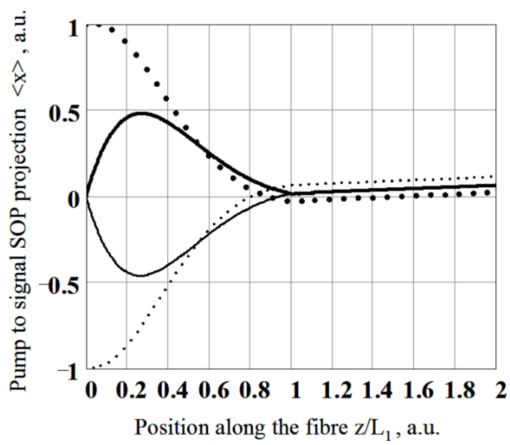

Figure 4. Evolution of the signal to pump SOP $\langle x \rangle$ for the case of two-section fibre. Minimum PDG: solid line; maximum PDG: dots. Projection for the maximum gain: thick solid line, thick dotted line; for the minimum gain: thin solid line, thin dotted line.

(PDG_0 is polarization dependent gain for FRA without pump depolarizer). Temperature fluctuations can lead to increased DOP for the input pump wave of 10-15% [10]. In view of this, it can result in increased PDG value above 1 dB. Thus, the suggested cost-effective approach to simultaneous mitigation of PMD and PDG based on two-section (without spin/periodically spun) fibre shows better results as compared to the results of application of pump depolarizer.

As follows from Fig. 2, the role of min and max PDG exchanges for two-section fibre. The Eq. (3) for a characteristic length of the first section of fibre without spin is an approximate and depends on the pump SOP (Fig. 4). It can lead to the swapping the pump SOPs corresponding to the max/min PDG with the increased spin rate. In addition, it results in PDG dependence on spin amplitude (Fig. 4).

4. Conclusions

In conclusion, we report a technique for simultaneous suppression of PMD and PDG in distributed fibre Raman amplifier based on application of two-section fibre. We have developed a procedure for evaluation of the correlation length and PMD value for the fist section to reach minimum PMD and PDG in two-section fibre. As a result, we obtained PDG = 0.3 dB and $D_p = 0.0072$ ps·km$^{-1/2}$ which are much better than the data for PMD reported in Ref. [7], namely $D_p = 0.032$ ps·km$^{-1/2}$.

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