

Characterization of Kerr nonlinearities in High Power Optical Amplifiers for free-space optical communications

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ABSTRACT

We propose a novel approach to measure the nonlinear phase shift that can occur in a high-power optical fiber amplifier (HPOA). This method consists in measuring, with a coherent optical receiver, the phase shifts experienced by a modulated optical signal propagating in an HPOA. This allows us to introduce the Kerr coefficient of an amplifier which gives the amount of nonlinear phase shift by unit of watt. We characterize the Kerr coefficient of a 10 W HPOA and show that its value strongly depends on whether the HPOA is used in a single-channel or a double-channel scheme.

Keywords: Free-space optics, high-power optical fiber amplifier, Kerr effect, Kerr angle, Kerr coefficient

1. INTRODUCTION

While free-space optical (FSO) links are now widely deployed commercially for optical inter-satellite links, significant challenges remain for longer distances, such as for inter-orbit or geostationary earth orbit (GEO) – ground transmissions. These longer links require for higher link budget, which in turn calls for the use of high-power systems such as beam combining [1] or high power optical amplifiers (HPOAs) [2], [3]. HPOAs are presently capable of delivering optical output powers ranging from a few watts to several tens of watts.

Nevertheless, a HPOA may bring nonlinearity, which leads to power penalties that may ultimately limit the benefits of its use [4], [5]. Among all sources of nonlinearity, Kerr effect plays a significant role. Kerr effect has been widely studied in terrestrial applications but remains little studied for space applications. In terrestrial applications, the transmitted optical power level is medium or low and the signals propagate over long fiber lengths, in dispersive media. While in HPOAs, the emitted power level is much higher, and signals travel very short distances in poorly dispersive media.

Penalties produced by Kerr effect can vary greatly depending on the system configurations (data rate, modulation, number of channels) and on the amplifier itself, its architecture and the characteristics of the doped fiber. A characterization of the Kerr nonlinearity produced by HPOAs is thus essential to compare different HPOA options, and to support the design of GEO-to-ground and ground-to-GEO optical communication systems.

In this article, we first recall some notions related to the Kerr effect and its manifestations. We study the impact Kerr effect on constellations. We introduce the Kerr coefficient to characterize the Kerr effect in HPOAs. Then, we propose a method to measure this new parameter. Finally, we present Kerr characterization measurements for a HPOA.

2. KERR EFFECT

When an optical field propagates through a dielectric medium, the induced electric polarization is generally described by a power series expansion of the electric field

$$\mathcal{P} = \epsilon_0 (\chi^{(1)} \cdot \mathcal{E} + \chi^{(2)} : \mathcal{E}\mathcal{E} + \chi^{(3)} : \mathcal{E}\mathcal{E}\mathcal{E} + \dots) \quad (1)$$

where ϵ_0 is the vacuum permittivity and $\chi^{(n)}$ denotes the n -th order electric susceptibility tensor. Under low optical intensities, the linear term dominates and the refractive index remains independent of the optical field. However, at the high optical powers delivered by modern fiber amplifiers, higher-order nonlinear terms become significant. Since silica is a centrosymmetric material, its second-order susceptibility vanishes $\chi^{(2)} = 0$, making the third-order susceptibility $\chi^{(3)}$ the dominant nonlinear contribution. This third-order nonlinear polarization gives rise to the optical Kerr effect.

The Kerr effect manifests itself as an intensity-dependent refractive index that can be expressed as

$$\tilde{n}(\omega, I) = n(\omega) + n_2 I \quad (2)$$

where $n(\omega)$ is the linear refractive index, n_2 is the nonlinear refractive index coefficient and I is the optical intensity. Consequently, the optical phase accumulated during propagation depends on the instantaneous optical power. The strength of the Kerr nonlinearity in an optical fiber is commonly characterized by the nonlinear coefficient

$$\gamma = \frac{2\pi n_2}{\lambda_0 A_{eff}} \quad (3)$$

where A_{eff} is the effective mode area and λ_0 is the operating wavelength in vacuum. As the optical power increases, the nonlinear phase shift accumulates along the fiber, leading to several nonlinear interactions that may significantly impair the quality of the transmitted signal.

The simplest manifestation of the Kerr effect is **self-phase modulation (SPM)**, in which a signal modulates its own phase through its instantaneous intensity, producing temporal chirp and spectral broadening. When several optical channels co-propagate within the same fiber, the intensity fluctuations of one wavelength also induce a phase modulation on neighboring channels, giving rise to **cross-phase modulation (XPM)**. If the interacting waves have different states of polarization, the nonlinear phase shift becomes polarization dependent, resulting in **cross-polarization modulation (XPoM)**, which may induce polarization fluctuations and additional signal distortions. Finally, the third-order susceptibility also enables **four-wave mixing (FWM)**, a parametric nonlinear process in which three optical waves interact to generate a fourth wave at a new frequency satisfying both energy and phase-matching conditions. In wavelength-division multiplexed systems, FWM may generate additional spectral components that overlap useful channels and contribute to nonlinear crosstalk. The relative contribution of these Kerr-induced effects depends on several parameters, including the optical power, channel spacing, chromatic dispersion, fiber length, effective mode area and state of polarization.

In the present work, particular attention is devoted to the Kerr nonlinear interactions occurring in the short fiber section of high-power optical amplifiers used for free-space optical communications.

3. NONLINEAR KERR ANGLE AND IMPACTS ON MONOCANAL COHERENT CONSTELLATIONS

3.1 Nonlinear Kerr angle and Kerr coefficient

For a system integrator like Thales Alenia Space, HPOAs are often seen as black boxes. Indeed, most of the time, we are not able to gather information on the architecture of the amplifiers, the characteristics and/or the length of the doped fibers used in the amplifier. To compare quantitatively the HPOAs in terms of the Kerr effect they generate, it is necessary to introduce a useful metric. When a signal propagates through a nonlinear medium, it experiences a nonlinear phase shift. We define the nonlinear Kerr angle as the maximum nonlinear phase shift experienced by a signal in the presence of SPM only. The expression of the Kerr angle is

$$K_a = \gamma L_{eff} P_{in} \quad (4)$$

where γ is the nonlinear coefficient, P_{in} the instantaneous power at the input of the medium and L_{eff} the effective length [1]. In an optical fiber the effective length depends on the loss of the fiber and is shorter than the real fiber length. In a gain medium, the effective length is longer than the doped-fiber length and depends on the gain parameter g . However, this gain parameter is a quantity to which we do not have access. It varies along the position z in the amplifier and also depends on the wavelength λ . For a gain medium such as an HPOA, it is more appropriate to define the Kerr angle K_a with respect to the output power P_{out} . The expression of the Kerr angle then becomes

$$K_a = \frac{\gamma L_{eff}}{G} P_{out} \quad (5)$$

where G is the gain of the system at a specific wavelength. We introduce the Kerr coefficient C_k , by dividing the Kerr angle K_a by the output power P_{out} . The Kerr coefficient has a dimension of an angle divided by a power [rad/W]. Its expression is

$$C_k = \frac{\gamma L_{eff}}{G} \quad (6)$$

The Kerr coefficient can be a useful metric to describe the amount of Kerr effect that an amplifier produces as a function of the amplified signal output power. On the other hand, the Kerr angle allows us to estimate the amount of Kerr effect that a signal undergoes as a function of the nonlinear Kerr-type effects to which it is subjected.

In the case where a signal only undergoes SPM, the resulting nonlinear phase shift corresponds to the Kerr angle. In a configuration with two channels, both channels experience a nonlinear phase shift due to SPM and XPM. The induced nonlinear phase shift corresponds to $3K_a$ if both channels have equal powers [1]. In a configuration with more than two regularly spaced channels, the signals may undergo FWM, which produces intra-channel crosstalk. We showed in [8] that it is possible to use the Kerr angle to determine the crosstalk seen by each channel in a WDM system. Table 1 and Table 2 give the coefficients to be applied to the Kerr angle in order to calculate the crosstalk of each channel, for a 3-channel and a 4-channel WDM system, respectively [8].

Table 1 : FWM crosstalk in a 3-channel WDM system

Channel number	1	2	3
Crosstalk X_n	$1K_a^2$	$4K_a^2$	$1K_a^2$

Table 2 : FWM crosstalk in a 4-channel WDM system

Channel number	1	2	3	4
Crosstalk X_n	$5K_a^2$	$9K_a^2$	$9K_a^2$	$5K_a^2$

3.2 Influence of the nonlinear phase shift on constellations

SPM and XPM produce a nonlinear phase shift which is related to the Kerr angle. For a telecom signal, this phase shift can be observed through the rotation of its constellation. To measure the link between Kerr angle and constellation rotation, we simulate the propagation of a QPSK 28 Gbaud signal and then a 16-QAM 28 Gbaud signal through a nonlinear medium using the nonlinear Schrödinger equation (NLSE) [1].

Instead of using an HPOA as the nonlinear medium, we simulate the propagation of the signal through a high nonlinear fiber (HNLf). We precisely control the signal power at the HNLf input. As in [8], the HNLf fiber allows us to emulate the nonlinear effects found in HPOAs. The emulator simplifies the study since it is a medium with no gain and no amplified spontaneous emission (ASE). The simulated fiber has a length of 512 m, linear losses of 0.69 dB/km, a non-linear coefficient γ equal to $11.3 \text{ W}^{-1} \cdot \text{m}^{-1}$ and a zero dispersion wavelength at 1550 nm.

Using expression (4), we vary the Kerr angle via the signal input power. Figure 1 shows QPSK constellation diagrams for Kerr angles of 0.049 rad, 0.15 rad and 0.47 rad. The ideal position of QPSK symbols without a Kerr angle is shown with red dots. The angle of rotation of each constellation corresponds to the respective values of angle Kerr that the QPSK signal undergoes. We notice that for a Kerr angle of 0.47 rad, the symbols have a slight longitudinal dispersion. This can lead to penalties on transmission performance. However, in a coherent link, digital signal processing (DSP) algorithms perform a phase recovery to compensate for the global or slowly variable phase rotations of the constellation. Thus, part of the phase rotation induced by the Kerr effect can be compensated by the DSP.

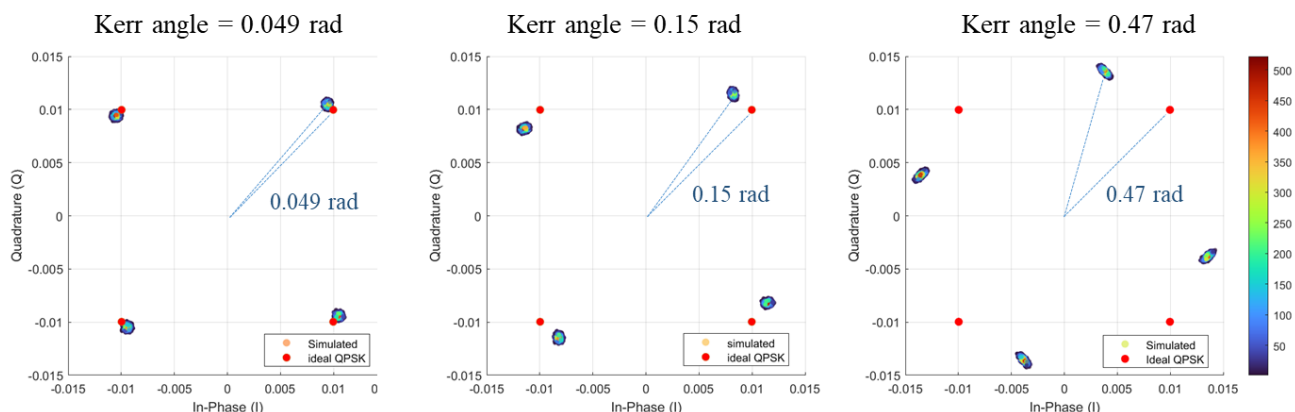


Figure 1: constellation diagrams of 28 Gbaud QPSK signal for several Kerr angles

We then simulate the propagation of a 16-QAM signal in the HNLf fiber. Figure 2 shows the constellation diagram for a signal with an average power of 15 dBm. The symbols of a 16-QAM signal are distributed over three power levels materialized by the concentric circles in Figure 2. A symbol with a low power level (red circle) undergoes little nonlinear

phase shift. The dispersion of the points is therefore low. On the other hand, a symbol on the outside of the constellation diagram (green circle) has a higher power. The SPM is more present and the resulting nonlinear phase shift is therefore greater. Since the nonlinear phase shift is not the same depending on the power level of the symbols, the rotation of the constellation is no longer uniform. Thus, unlike the case of a QPSK signal, a global phase correction does not allow to simultaneously compensate for the phase shift experienced by all symbols. An optimal compensation would need to take into account the dependence of the phase shift on the power of the symbol. This differential rotation of the different levels of the constellation thus contributes to the deformation of the constellation and can lead to a degradation of transmission performance.

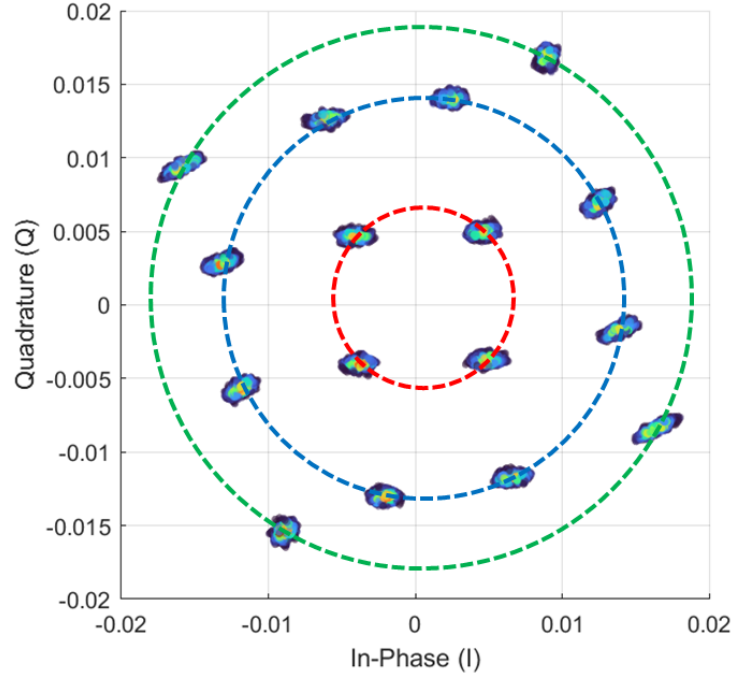


Figure 2: constellation diagram of 28 Gbaud 16-QAM signal for $P_{in} = 15$ dBm

4. METHOD FOR MEASURING THE KERR ANGLE BASED ON COHERENT DETECTION

The method for measuring the Kerr angle in a doped-fiber amplifier is based on the method for measuring the nonlinear coefficient in a fiber, as reported in Ref. [8]. The proposed method is based on the phase measurement of a modulated signal, thanks to a coherent receiver. The experimental setup is shown in figure 3.

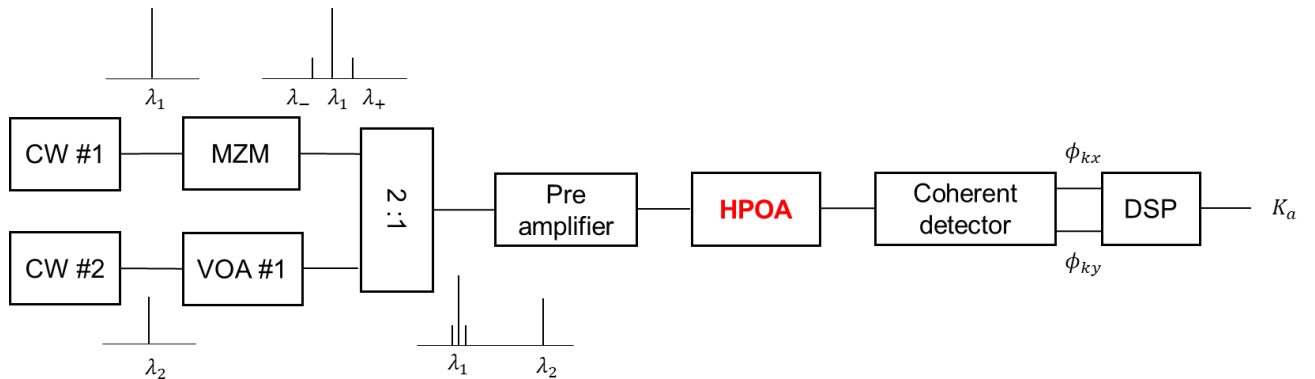


Figure 3. Setup for measuring the Kerr angle using heterodyne coherent detection

A single-frequency continuous wave laser (CW #1) delivers at the wavelength λ_1 . The laser is amplitude modulated by a Mach-Zehnder modulator (MZM) with a sinusoidal wave at a frequency of 2 GHz. The modulation index being low, the signal spectrum consists of a main line with two sidebands with lower amplitude.

In order to carry out a measurement of the Kerr angle as a function of the modulated signal power, while operating the HPOA under test at a constant output power, a second single-frequency continuous-wave laser (CW #2) is used to load the HPOA under test. Its wavelength λ_2 is shifted by $\Delta\lambda$ relatively to λ_1 . The optical variable attenuator (VOA #1) allows us to adjust the signal power at λ_2 . The signals at λ_1 and λ_2 are then combined using a 3 dB coupler. A preamplifier with a maximum output power of +15 dBm allows us to control the total average power injected into the HPOA under test.

The output power of the HPOA is distributed over both signals at λ_1 and λ_2 according to their relative power at the input, as well as on the optical gain shape of the HPOA. Depending on the input power P_2 of laser CW #2, the total output power of the amplifier can be either equitably distributed between both signals or be entirely in the signal at λ_1 .

At the output of the HPOA, a coherent receiver is used to detect and analyze the modulated signal. This device, usually used for coherent communications, enables to detect the amplitude and phase of the heterodyne beating between an optical signal to be measured and a continuous laser called local oscillator. In our case, the signal to be measured is the modulated signal at the output of the HPOA under test and the local oscillator is a DC laser shifted by 200 MHz compared to the signal at λ_1 (not represented in figure 3).

During amplification, each of the three lines of the modulated signal undergoes a phase shift due to SPM, XPM and FWM. The coherent receiver allows us to measure the phase ϕ_1 of the carrier frequency and the phases ϕ_+ and ϕ_- of the two sidebands separately. However, these three phases also contain the phase noise of the laser CW #1, that of the local oscillator and possible other disturbances related to the measurement environment. An individual measurement of the phase of these three lines therefore does not allow measuring the phase shift due to nonlinear effects. To eliminate random phase fluctuations, we introduce the quantity $\Delta\phi$ corresponding to a combination of the phases of the three lines of the modulated signal. This quantity equals

$$\Delta\phi = \phi_+ + \phi_- - 2\phi_1 \quad (7)$$

In the absence of nonlinear effects, this quantity equals to zero. From the equations of degenerate FWM [1] and assuming that the nonlinear effects are small, we found that the quantity $\Delta\phi$ can be written as

$$\Delta\phi = 4\gamma L_{eff} P_{in} + \beta_2 \Delta\omega^2 L \quad (8)$$

where P_{in} can be considered as the average input power of the modulated signal in the case of a very low modulation index (which is the case in practice), β_2 is the second order dispersion and $\Delta\omega$ is the frequency spacing between waves. In a fiber amplifier, the fiber lengths are relatively short (of the order of a few meters or tens of meters). It is therefore reasonable to consider that dispersion factor $\beta_2 \Delta\omega^2 L$ is negligible.

Therefore, in the following, we will assume that the quantity $\Delta\phi$ in a fiber amplifier is simply

$$\Delta\phi = 4\gamma L_{eff} P_{in} \quad (9)$$

We directly identify that the quantity $\gamma L_{eff} P_{in}$ corresponds to the Kerr angle. Therefore, the proposed method allows us to access to the Kerr angle via the measurement of $\Delta\phi$. We can therefore write

$$\Delta\phi = 4K_a \quad (10)$$

By knowing the Kerr angle and by measuring the output power, we can determine the Kerr coefficient according to Eq. (5).

5. NONLINEAR CHARACTERIZATION OF A HPOA

The tests are carried out on a polarization-maintaining (PM) erbium-ytterbium-doped fiber amplifier capable to deliver a total output power of 10 W. We measure the Kerr angle K_a with the method presented in section 4 at two different wavelengths: 1539.8 nm, and 1553.3 nm. By dividing K_a by the output power P_{out1} of the considered wavelength, we deduce the value of the Kerr coefficient C_k according to Eqs. (5) and (6). Since P_{out1} can be varied by loading a second channel with a variable input power, we can also study the evolution of C_k as a function of P_{out1} . Figure 4 shows the overall spectrum at the output of the amplifier for both measurements. One measurement is performed at 1553.3 nm and the other one at 1539.8 nm. In both cases, the second power-varying laser is positioned at $\Delta\lambda = \pm 0.4$ nm from the first one (only the cases $\Delta\lambda = -0.4$ nm are represented in figure 4). Note that FWM idlers are also visible in figure 4 but will not be considered in the following.

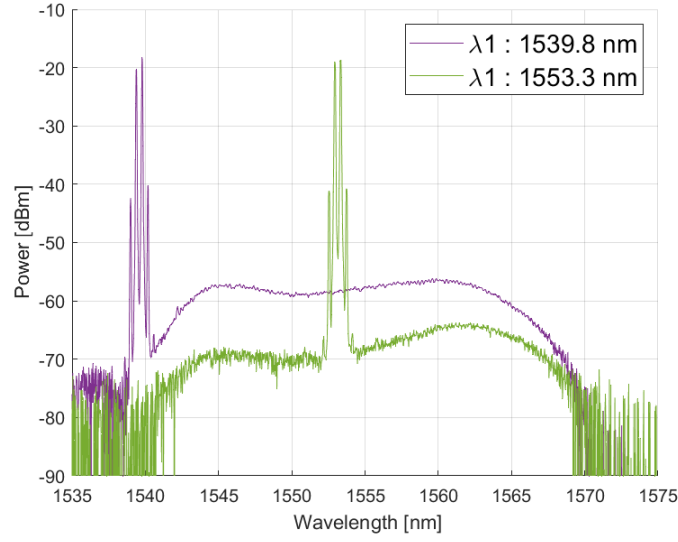


Figure 4: HPOA output spectrum

Figure 5 shows the evolution of the Kerr angle K_a as a function of the output power P_{out1} for the wavelength $\lambda_1 = 1553.3$ nm. The maximum value of 0.13 rad is reached when the second laser at $\lambda_2 = 1552.9$ nm is off. When its power is increased, the power P_{out1} decreases and causes the value of K_a drop. The evolution of K_a seems linear.

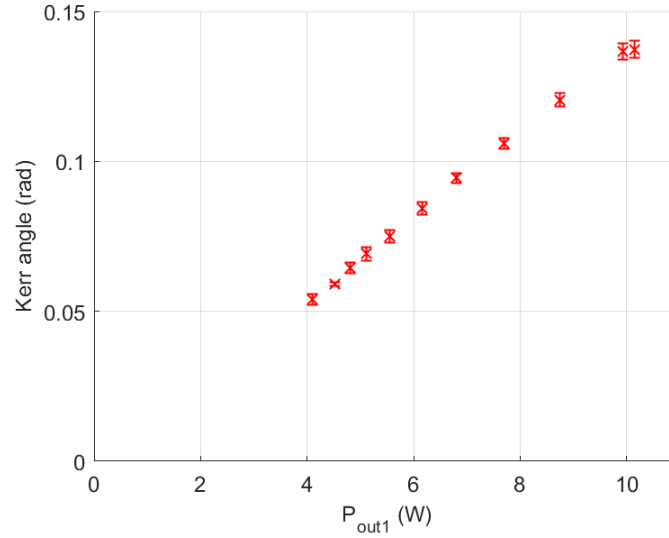


Figure 5: Kerr angle measurements at $\lambda_1 = 1553.3$ nm

Figure 6 shows the evolution of C_k as a function of P_{out1} for the same wavelength $\lambda_1 = 1553.3$ nm in the following two cases. The second laser is either downshifted or upshifted by 0.4 nm from the wavelength 1553.3 nm. The Kerr coefficient C_k is very similar in both cases and can be considered as almost constant with respect to the output power. Note that this measurement at 1553.3 nm corresponds to the case where the gain profile (visible on the ASE profile of figure 4) is relatively flat.

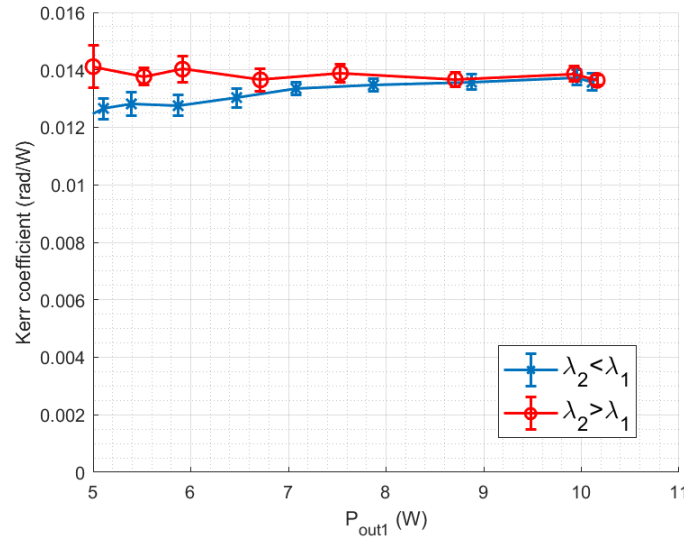


Figure 6: Kerr coefficient for $\lambda_1 = 1553.3$ nm

Figure 7 now represents the evolution of C_k for $\lambda_1 = 1539.8$ nm, i.e. on the edge of the gain profile of the amplifier. Here again, the cases in which the second laser is downshifted or upshifted by 0.4 nm are examined. We now clearly note that the Kerr coefficients are different in both cases and show completely different trends. When $\lambda_2 > \lambda_1$ the Kerr coefficient decreases with the output power of λ_1 while it increases when $\lambda_2 < \lambda_1$. When the output power of λ_1 is around 5 W for example (i.e. when the two channels have approximatively equal powers) the Kerr coefficient can be 0.0085 rad/W or 0.0162 rad/W depending on whether the second channel is downshifted or upshifted. This result is the key finding of our study and can be explained by the cross-gain saturation effect of the amplifier.

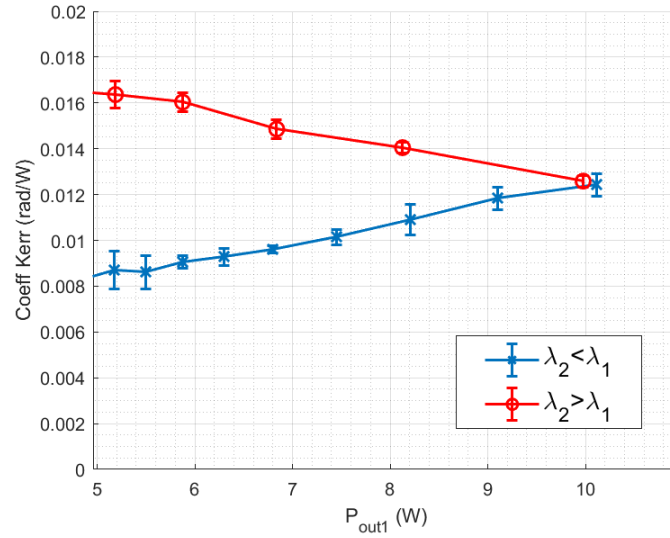


Figure 7: Kerr coefficient for $\lambda_1 = 1539.8$ nm

Two phenomena have to be taken into account to explain this behavior. First, the gain is saturated by the signal power. Secondly, the gain is strongly wavelength-dependent because of the wavelength dependence of the absorption and emission cross-sections. In consequence, the growth of the power at one wavelength can decrease the gain at another wavelength if the gain at the growing wavelength is higher than the other one. Conversely, it can increase the gain at the other wavelength if this one has a higher gain than the growing wavelength. This effect has been measured in the HPOA.

Figure 8 represents the evolution of the gain at $\lambda_1 = 1539.8$ nm as a function of the power P_{out1} at this wavelength when the power of the second wavelength λ_2 is varied. A growth of the power of λ_2 always leads to a decrease of the power P_{out1} at λ_1 but the gain at λ_1 depends on which side is λ_2 . When the wavelength λ_2 is lower than λ_1 , the gain at λ_1 increases when the power decreases. In the case where λ_2 is greater than λ_1 , the gain at λ_1 decreases when the power P_{out1} decreases. Since the Kerr coefficient C_k is strongly dependent on the gain through both L_{eff} and G , according to Eq. (6), it also follows a similar behavior. The evolution of gain in figure 8 thus explains the evolution of the Kerr coefficient of figure 7.

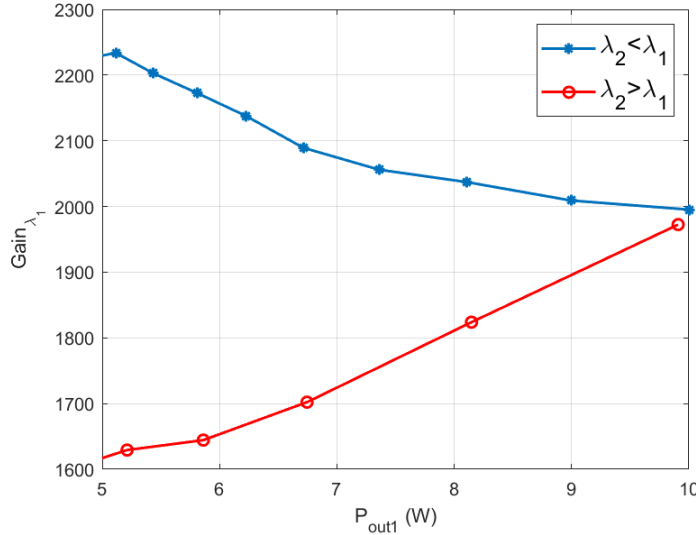


Figure 8: Gain evolution of λ_1 as a function of the output power of λ_1 and according to the position of λ_2

This study shows that, even if the Kerr coefficient can easily be measured in a single-channel configuration in a HPOA (using for example the method proposed in [8]), special attention must be paid when two (or more) channels are involved. Depending on the location of the channels within the gain profile of the amplifier, the Kerr coefficient can vary in the ratio of one to two with direct consequences on the system performances of FSO links.

6. CONCLUSION

In order to characterize the Kerr-like nonlinearities produced by HPOAs, we introduced two parameters: the Kerr angle and the Kerr coefficient. We have shown the impact of the Kerr angle on QPSK and 16-QAM constellations. We presented a method to measure these parameters, and highlighted the results of nonlinear Kerr-type characterization obtained on a 10 W PM HPOA. Measurements on the HPOA show that the non-uniformity of the gain profile of the amplifier complicates the characterization of the Kerr effect for two channels or more. The design of future WDM FSO links will therefore require significant development.

ACKNOWLEDGEMENTS

The authors thank Région Bretagne, Ministère de l'Enseignement Supérieur et de la Recherche and the European Fund for Regional Economic Development for their financial support to the CPER Phot-Breizh program.

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