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Transient analysis of a nonlinear fiber ring resonator

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In this letter we study the transient behavior of a nonlinear fiber ring resonator operating both as an optical bistable and as a differential amplifier. The speed of response of the structure is investigated, and some general considerations on the performance of these kinds of devices are presented.

The operation of a nonlinear fiber optical resonator as a passive optical bistable was first demonstrated theoretically by Crosignani *et al.*,[1] who studied a cross-coupled architecture. Recently, several articles have been published which consider a different structure: The nonlinear two-coupler ring resonator (TCRR). In Ref. 2, a geometrical method was used to obtain a simple description of the bistable operation of the TCRR. This method, which provides great insight into the influence of the various parameters of the device on its behavior, was extended in Ref. 3 to the analysis of the TCRR as an optical differential amplifier. Also, the bistability of a TCRR using degenerate two-wave mixing has been studied in Ref. 2.

However, all the work mentioned above has focused exclusively on the stationary characterization of the TCRR (pure sinusoidal input). Indeed, the TCRR will always operate with time-varying signals (for example, as a pulse-amplifying device), so the knowledge of its transient behavior is essential for a realistic description. This letter addresses, for the first time to the authors' knowledge, the transient effect of a nonlinear fiber resonant structure.

The TCRR is depicted in its most general form in Fig. 1. The triangle represents a doped-fiber amplifier of power gain G. For the moment, we shall set $G=1$ and ignore it. If the fibers, of lengths L_a and L_b, were linear, the structure would simply operate as a linear optical filter with an intensity transmissivity function

$$\left|\frac{E_{\text{out}}}{E_{\text{in}}}\right|^2 \equiv y(\Phi) = \frac{T_1 T_2 \exp(-2\alpha L_a)}{(1-\sqrt{\chi_1\chi_2})^2 + 4\sqrt{\chi_1\chi_2}\,\sin^2(\Phi/2)}, \quad (1)$$

where $\Phi=\beta L \equiv (L_a+L_b)$ is the linear phase shift, α is the fiber attenuation, and χ_1, χ_2, T_1, and T_2 are parameters which depend on the insertion losses of the couplers, their coupling constants, L_a and L_b, and α.[5] The nonstationary response of such a device can be obtained very easily for any arbitrary input field by means of standard fast Fourier transform (FFT) computations. The fiber dispersion can be accounted for by including the second and higher-order terms in the Taylor expansion of $\beta(\omega)$. Nevertheless, the short length of the optical circuit makes dispersion effects completely neglectable, as can be easily checked. Therefore the transient effects arise solely from the propagation delays.

If the fibers of the ring have Kerr nonlinearity, Eq. (1) is still valid provided the phase is redefined as (refer to Fig. 1)

$$\Phi = \beta L + R L_a |E_a|^2 + R L_b |E_b|^2, \quad (2)$$

with R the nonlinear phase-shift coefficient.[1] It should be pointed out that Eq. (2), used previously in the literature, implicitly assumes that the attenuation of the nonlinear fibers is very small. Indeed, the general solution of the nonlinear Schrödinger equation with no dispersion shows that the nonlinear phase shift at the end of a fiber of length L is proportional to $|E(\tau)|^2(1-e^{-\alpha L})/\alpha$, with $E(\tau)$ the (time-retarded) input field amplitude. Only if $\alpha L \ll 1$ is expression (2) valid. Now it can be shown that expressions (1) and (2), the latter of which is power dependent, describe bistable behavior[2] or differential amplification.[3]

The study of the TCRR cannot make use of the transference function formalism since the device is no longer a linear system. The signal must now be tracked along its successive recirculations around the ring, and, in principle, a nonlinear beam propagation method (BPM)[6] should be used for the nonlinear sections. However, the fact that the dispersion effects are negligible allows to use the analytical solution of the propagation equation, eliminating the need for the BPM altogether. This simplification is more important than it might seem, because the BPM method requires the input field at all times, but this is not easily known in this case because of the recirculations.

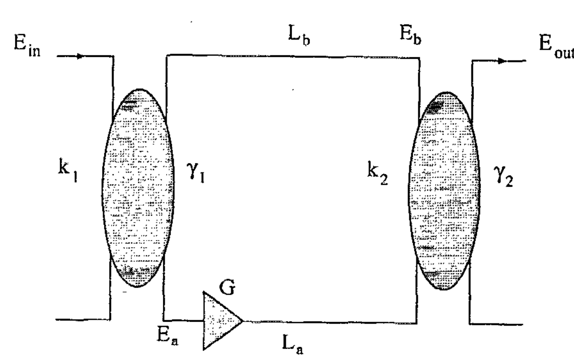

FIG. 1. Nonlinear double coupler fiber ring resonator of total length L_a+L_b. k_i and γ_i ($i=1,2$) are the coupling constants and insertion losses of the couplers. G is an (optional) optical amplifier.

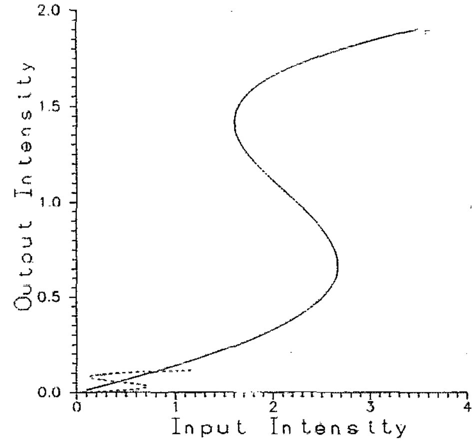

FIG. 2. Stationary transmission characteristics of a TCRR with $\alpha=0.04$ and $\gamma=0.02$. Solid line: $\beta(L_a+L_b)\equiv\beta L=1.27\pi$ and $k_1=k_2\equiv k=0.5$. Dashed line: $\beta L=1.75\pi$ and $k=0.1$.

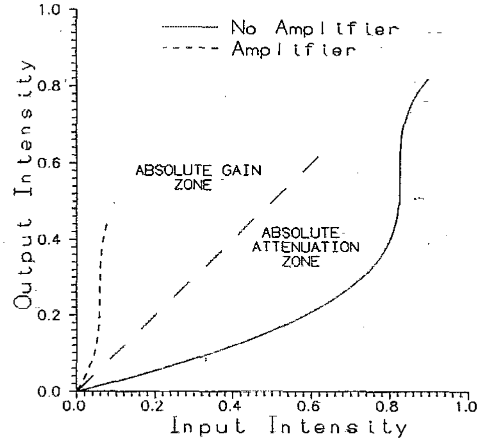

FIG. 4. Stationary transmission characteristics of a TCRR operating as a differential amplifier, both passively and incorporating an in-loop amplifier with $G=3.25$ dB. Note that there is an infinite slope point in each of the curves. βL, appropriately chosen to obtain these critical points, is 1.59π and 1.81π, respectively. α and γ are as in Fig. 3, and $k=0.5$.

Figure 2 shows the stationary output-input characteristics of a TCRR for two different bistability conditions. Figure 3 shows the actual output for the case corresponding to the largest hysteresis loop in Fig. 2, when the input (normalized intensity[1]) varies from 0 to 3 with a rise time of 50 ns. A group velocity $v_g=2.4\times10^8$ m/s and $L_a=L_b=8$ cm were taken. According to the stationary results (Fig. 2), the bistable should pass from the off to the on state. In Fig. 3, the switch-on point would be the value of the input power for which the output starts to grow more abruptly. In fact, as seen in the figure, it is not possible to identify such a unique, well-defined point; rather, there is a narrow margin of input intensities which would quality to be defined as the switch-on point. However, any value in this margin is very close to that predicted by the stationary calculations (2.65 in this case; the corresponding value of the output is indicated in Fig. 3 by an asterisk). Naturally, the jump of the output power is not instantaneous.

The final output power coincides with the stationary value, ~1.84, as expected (see Fig. 2). Notice from Fig. 3 that the time it takes the output to settle at its final value is ~10 ns. This is of the order of 10–15 times the loop delay, which is about $(L_a+L_b)/v_g\cong0.67$. The reason is that there must be appreciable interference between the input and the output for one of these devices to operate properly (that is, in a *quasistationary* fashion). A similar on-off transition is also shown in Fig. 3.

The TCRR can also operate as an optical differential amplifier (DA), and some analytical expressions for the significant parameters of such a device have been obtained.[3] Among these is the necessary input power to obtain infinite differential gain (*bias power*). The solid curve in Fig. 4 is a typical output-input characteristic of a passive DA. The left side of Fig. 5 clearly illustrates the amplification of a ~100 ns pulse, which enters the passive TCRR superimposed to the corresponding bias power (0.83, in this case). We see that an extremely long tail accompanies the output pulse. This would generate symbol interference when transmitting sequences of pulses, thus representing a serious handicap. Further calculations have shown us that this phenomenon is always present in normal operating conditions, *independently of the width* and amplitude of the

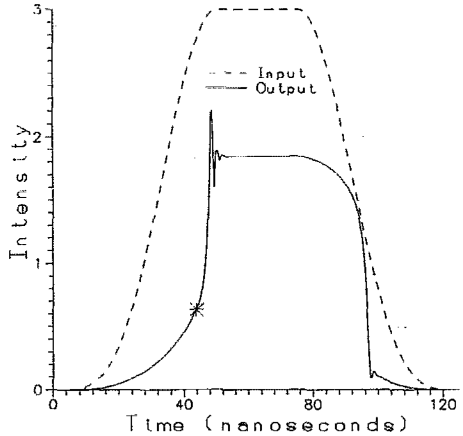

FIG. 3. Dynamic behavior of a bistable under on and off transitions. The parameters are those of the case represented by a solid line in Fig. 2.

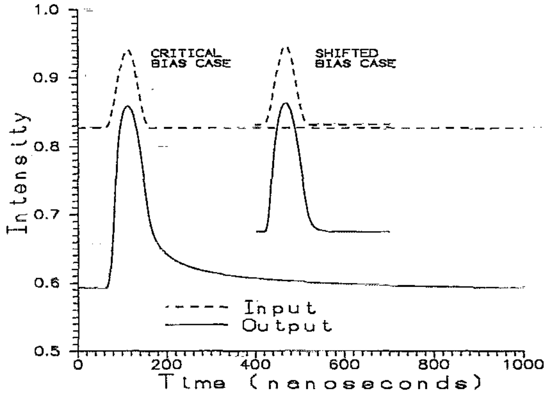

FIG. 5. Pulse amplification of the passive DA of Fig. 4. $L_a=L_b=8$ cm. Left: Critical bias power. Right: Shifted bias power.

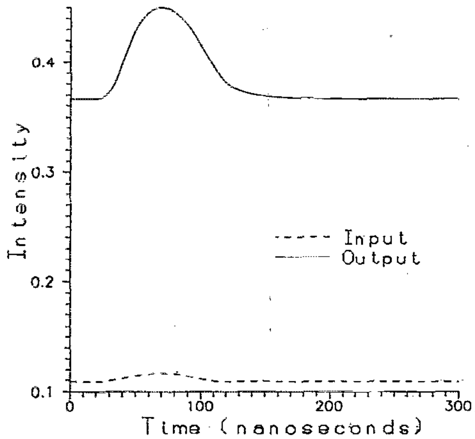

FIG. 6. The output of the active DA is shown for an input pulse of the same length as in Fig. 5. The bias of the active structure was also slightly shifted from its critical point (+0.0005).

input pulse. It is related to the fact that the input returns to the bias power after the pulse has passed. By slightly shifting the bias power above or below the finite gain point, the tail effect is eliminated, as shown in the right of Fig. 5, where the bias was increased in 0.005. (However, the shift should not be too large, because the differential gain generally reduces very quickly as the input power moves away from the infinite gain point; the extent of this reduction depends on the coupling constants.)[3] It should be stressed that the tail is eliminated in this way even though the excursion of the pulse amplitude reaches or even crosses the critical point: Only the final value (bias power) is relevant.

The inclusion of an in-loop active amplifier, as in Fig. 1, has been shown to significantly reduce the bias power.[7] The stationary input-output characteristic in this case is the dashed line in Fig. 4. The possibility of operation with absolute gain is also evident. The effect of the active amplifier on the transient characteristics of the DA is presented next. For simplicity and ease of comparison, we assume the active amplifier to have zero length, so that its contribution is simply accounted for by a power gain G. (Assuming finite length and a propagation constant such that the phase shift at the central optical frequency is a multiple of 2π would also be equivalent to modeling the amplifier as a lumped-gain element, although only at that frequency.) This simplification does not affect the generality of the results.

Figure 6 shows the output of the active differential amplifier for an input pulse of the same length as in Fig. 5. Apart from the absolute-gain feature and the requirement of smaller bias power (already evidenced in Fig. 4), it is evident that the active structure also provides larger differential gain. It can also be seen that the response of the active device is somewhat slower than that of the passive one (compare with Fig. 5, shifted bias case). This is due to the presence of the in-loop amplifier, which enhances the amplitudes of the recirculating fields. In this way more recirculations must take place before their amplitudes become negligible, and thus the transient behavior is worse.

If the input pulse is too narrow the interference disappears, the role of the nonlinearity becomes irrelevant, and the device operates simply as a linear delay cell with feedback.[8]

In conclusion, we have seen that the TCRR can be analyzed realistically without taking into account the fiber dispersion, which simplifies its numerical study significantly. Its speed of response, and therefore its utility, is almost exclusively determined by the length of the loop. Currently, this imposes a serious limitation because the normalized powers are proportional to the length of the fibers in the loop. For example, with a nonlinear index coefficient $n_2=5\times10^{-20}$ m^2/V^2 and $L_a=L_b=80$ cm, a normalized power of 1 is equivalent to an actual power of 0.11 W,[3] and further reduction of the fiber length causes the values of required powers to increase accordingly. However, very short loops are needed if the device is to operate with fast signals or short pulses. Crudely, a reduction of the loop length by a factor allows the same reduction of the pulse lengths. If we wish the DA to work with, say, 10 ns pulses, a total loop length of $\sim$10 cm should not be exceeded. The only solution seems to rely on using integrated optics with strongly nonlinear materials, as the normalized power is also proportional to n_2. A shorter loop would also relax the constraint on the coherence length of the optical source.

It has also been seen that there is a certain trade-off between the bias power of a DA and its speed of response when an in-loop active amplifier is used, although the degradation of the latter is reasonably small.

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