Measurements of Thermal Effects in Fibers Doped with Cobalt and Vanadium

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***Abstract*—Thermal index changes due to nonradiative relaxation in optically pumped Co^{2+}-doped and V^{n+}-doped fibers are studied experimentally by an interferometric method. In both dopants these effects are shown to be very strong and to mask any residual resonantly enhanced nonlinearity. The measured magnitude and time constants of thermal effects are well explained by a new theoretical model, which confirms its validity and usefulness. These measurements also demonstrate a new and simple method to differentiate between nonlinear and thermal phase shifts in doped fibers based on the dependence of the phase change on the pump pulsewidth. This study provides new information on the spectroscopy of these two dopants, including the percentage of absorbed power they transform into heat (~38% for Co^{2+} and 56% for V^{n+}), and the likely presence of clusters in Co^{2+}-doped silica even at very low concentrations (8 wt ppm CoO).**

***Index Terms*—Cobalt, interferometry, nonlinearities, optical fiber amplifiers, optical fiber attenuators, optical fiber lasers, optical fiber switches, optical pumping, temperature, thermal factors, vanadium.**

I. Introduction

PUMP-INDUCED thermal effects in doped fibers due to nonradiative processes are detrimental in most doped fiber devices, including high power lasers and amplifiers. They induce a temperature change in the fiber, which can result in thermal damage and/or a phase change that can be undesirable, especially in phase-sensitive devices such as interferometers and nonlinear switches [1]. To assess the magnitude of these effects, we have recently developed a new theoretical model that analyzes both the transient and steady-state thermal effects caused by either a single pump pulse, multiple pump pulses, or a continuous-wave (CW) pump [2]. This study is particularly relevant to switches based on a resonantly enhanced nonlinearity. When a doped fiber is optically pumped, its ground state is depleted, which changes its absorption and thus, via the Kramers–Krönig causality principle, its refractive index [1]. This effect can be extremely strong, and it has produced fiber switches with record low switching power [1], [3]. In such devices, thermally induced phase changes can compete with the nonlinear phase change [4], which must be avoided by careful selection of the dopant.

In this paper we describe experimental measurements of thermally induced phase changes in fibers doped with a transition metal ion, namely, Co^{2+} or V^{n+}. Our objectives were first to measure quantitatively the magnitude and dynamic response of temperature changes in doped fibers by means of their impact on the phase of a signal traveling through the fiber; second, to verify the validity of our theoretical model; third, to demonstrate experimentally a new method to differentiate nonlinear from thermal phase changes in a doped fiber; and finally, to shed new light on the spectroscopy of cobalt-doped and vanadium-doped glasses and assess their usefulness as a nonlinear dopant.

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II. Theory

In an optically pumped fiber, the energy absorbed by the dopant is ultimately transformed partly into fluorescence via radiative relaxation processes, and partly into heat via nonradiative relaxation processes. The fraction η of absorbed energy turned into heat depends on the relative time constants of these two processes [2]. It is zero for a purely radiative relaxation, and unity for a dominantly nonradiative relaxation. Two distinct pumping regimes must be considered. In the instantaneous regime, the fiber is pumped with a single, short pump pulse (or pulses that are very widely spaced in time). The heat deposited in the doped core first causes an increase in the core temperature. Then as the heat diffuses into the cladding the core cools down and the temperature distribution widens, extending from the core across part of, and eventually all of, the cladding. If the pump pulse is extremely short, the rise time of the core temperature, and of the associated core index change, depend on the nonradiative relaxation rate, which can be in the nanosecond range or less, depending on the dopant spectroscopy [2]. The fall time, on the other hand, is imposed by the rate of heat flow into the cladding. Assuming a Gaussian distribution with a $1/e$ radius r_0 for the temperature in and around the core just after the delivery of the pump pulse (which is essentially equal to the pump radius), and a Gaussian mode with a $1/e$ radius r_s for the signal propagating through the fiber, the 50% thermal relaxation time constant of the phase shift due to this temperature distribution is given by [2]

$$\tau_{\rm th} = \frac{r_0^2 + r_s^2}{4D} \tag{1}$$

where D is the thermal diffusivity of the fiber material. After a time $t \gg \tau_{\rm th}$, all of the heat has diffused through the cladding (and possibly jacket) and into the surrounding medium (usually air), and the temperature of the entire fiber is back to room temperature. If the pump pulse is lengthened, we expect the temperature profile at the end of the pulse to widen, i.e., r_0 to increase, and thus the fall time to increase [see (1)]. This is contrary to

the resonantly enhanced nonlinear index, for which the fall time is equal to the dopant excited state lifetime and independent of pulsewidth [1]. We show further on that this difference can be exploited to distinguish these two effects.

In the steady-state regime, the pump is either composed of a continuous train of pulses or CW. Over time, the heat deposited in the core accumulates in the fiber core and cladding, and its temperature rises. For a fiber cooled by natural air convection, at steady-state the temperature is very nearly uniform across the fiber [2]. However, each individual pulse continues to cause a short burst in the core temperature. Our model predicts, among other properties, the average temperature rise of the fiber and the temporal evolution of the thermal phase change experienced by a signal traveling through the fiber.

To verify the validity of these predictions, we characterized fibers doped with a transition metal. Transition metals exhibit strong absorptions [5] and are thus natural candidates for nonlinear dopants. In this work, we studied cobalt and vanadium, which are readily available in a fiber form. The parameters of the fibers we tested are listed in Table I. The concentrations were determined from experimental spectra using the method of [5]. Fig. 1 shows the measured absorption spectrum of Co-doped fiber #1. It exhibits a strong absorption below about 750 nm, a more modest absorption above about 950 nm, and a transparency window in the vicinity of 800 nm. This spectrum is similar to that of [5], and it is consistent with the wide absorption bands of Co^{2+} in crystalline MgF_2, illustrated in Fig. 2 [6]. This diagram suggests that a fiber pumped near 700 nm will exhibit a high percentage of nonradiative intraband relaxation.

TABLE I
PARAMETERS AND EXPERIMENTAL CONSTANTS OF THE CO-DOPED AND V-DOPED FIBERS. MEASURED VALUES OF THE CONSTANT η WERE OBTAINED WITH A PUMP THAT WAS EITHER (1) CHOPPED, (2) ELECTRO-OPTICALLY MODULATED, OR (3) CW

Fiber	Concentration (wt ppm oxide)	Core radius (μm)	Numerical aperture	Length (cm)	η
Co #1	10600	2.9	0.178	0.18	$0.35\pm0.1^{(1)}$ $0.45\pm0.05^{(2)}$
Co #2	2930	3.7	0.128	0.8	$0.32\pm0.04^{(2)}$
Co #3	8	3.6	0.13	100	$0.34\pm0.02^{(2)}$
V #1	16	3.5	0.14	83.5	$0.56^{(3)}$

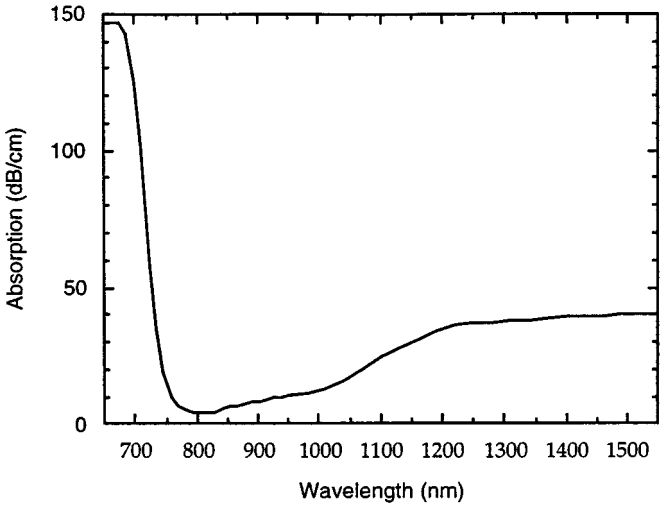

Fig. 1. Absorption spectrum of Co-doped fiber #1.

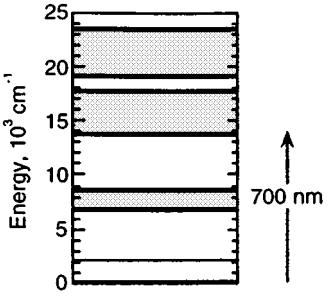

Fig. 2. Partial energy level diagram of Co^{2+}-doped crystalline MgF_2 (after [6]).

III. MEASUREMENTS IN COBALT-DOPED FIBERS

To measure pump-induced temperature changes, we spliced a short length of doped fiber in one of the arms of a fiber Mach–Zehnder (MZ) interferometer to map thermal phase modulations into intensity modulations (see Fig. 3) [4]. The MZ was constructed with two nominally identical fused fiber couplers. The signal (wavelength $\lambda_s = 830$ nm) was provided by a laser diode. Its coherence length was short, which required that the two arms of the MZ have nearly equal lengths. To this end, the length of one of the arms was adjusted by stretching it with a pulling stage. The pump source was a Ti:sapphire laser operated in the 700–720 nm range. The pump power was modulated using either an external mechanical chopper (to produce pulses in the 100–500 μs range), an external electro-optic modulator (5–30 μs), or Q-switching (~25 ns pulses). The signal and pump were counterpropagated to eliminate the need for a filter at the signal output port (port 4). Some of the fiber ends were angle polished (see Fig. 3) to eliminate spurious back reflections into port 4. The polarization beam splitter (PBSC) and the polarization controller PC_2 were used to minimize pump power reflected off the front facet of the laser diode. The coupling ratio of the couplers was 0.66 near 700 nm and 0.45 near 830 nm. The transmitted pump power was monitored with a silicon photodetector at port 2. This setup enabled us to measure both the magnitude and dynamics of the thermal index changes induced in the fiber under various pumping conditions.

Fig. 4 shows a typical experimental trace of the temporal dependence of the instantaneous thermal phase change, measured in Co-doped fiber #2 (solid experimental curve) pumped with a single 15-μs pump pulse (dashed curve). The thermal phase increases during the pump pulse, then decays at a slower rate when the pump pulse is off. The 50%-fall time is 9.4 μs. The smooth solid curve in Fig. 4 is theoretically predicted from our model. The only fitting parameter used to generate it is the amount of heat generated in the fiber (which only scales the phase), which depends on the unknown parameter η. Both the falling and rising edges agree quite well with observations.

This measurement was repeated for pump pulsewidths ranging from 5 to 500 μs and both the thermal phase change

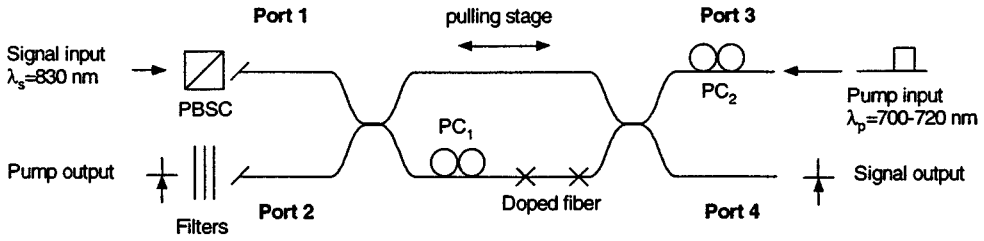

Fig. 3. Experimental fiber Mach-Zehnder interferometer used to measure thermally induced phase shifts in fibers doped with transition metals.

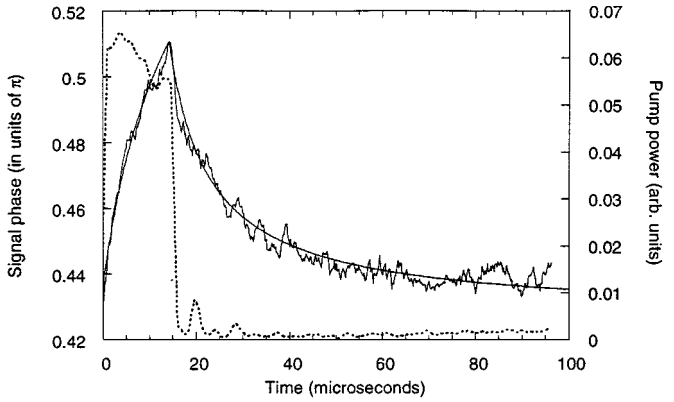

Fig. 4. Temporal dependence of the thermal phase shift at 830 nm generated by a 15-μs pump pulse at 720 nm in an 8-mm length of Co-doped fiber.

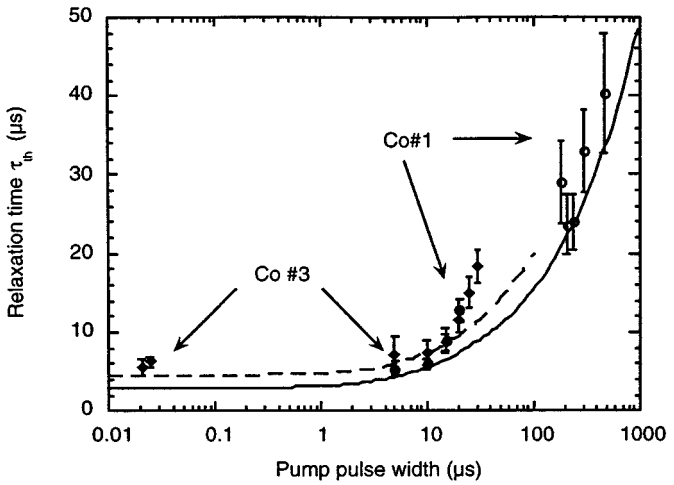

Fig. 5. Fall time dependence of the thermal phase shift on pump pulsewidth, measured for Co-doped fibers #1 and #3. The solid and dashed curves are the theoretical dependencies calculated for fibers #1 and #3.

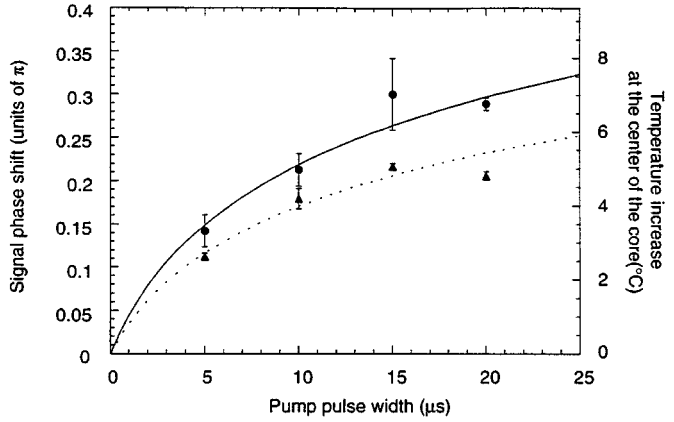

Fig. 6. Measured peak phase shift as a function of pump pulsewidth for Co-doped fiber #1. Absorbed pump power was 136 mW for the filled triangles, and 214 mW for the circles. The second vertical axis represents the temperature at the center of the core. The solid curves are simulations.

and the fall time $\tau_{\rm th}$ were recorded versus pulsewidth. The fall time dependence, measured for two fibers, is plotted in Fig. 5. The error bars represent standard deviations of the data points, which were measured several times and averaged (the error is larger for larger pulses due to noise sources related to the chopper). As expected from basic principles, and from (1), the relaxation time constant increases with increasing pump pulsewidth. The minimum time constant (for pump pulses shorter than about 1 μs) is around 5 μs. The solid and dashed curves in Fig. 5 are the dependencies calculated for fiber #1 and #3, respectively. The input parameters used to generate these curves are the fiber core radii and NA's, and the signal wavelength. Pump absorption was assumed uniform across the core, which is reasonable given that pump absorption is saturated. The experimental data agree well with the model. The systematic difference between theory curves and experimental data points (a factor of $\sim$1.4) is most likely linked to the model assumptions of step-index profiles for the signal mode and the dopant profile, which both tend to narrow the radii r_0 and r_s and thus reduce $\tau_{\rm th}$ [see (1)].

Fig. 6 plots the measured peak phase shift as a function of pump pulsewidth for fiber #1. The filled triangles were obtained with an absorbed pump power of 136 mW, and the circles with 214 mW. The curves are phase shift simulations generated from [2], using η as the only fitting parameter. The vertical axis on the right hand side shows the temperature increase at the center of the core $(r = 0)$, predicted by (24), [2] when the phase shift (predicted by (16) [2]) best matches the measured peak phase shift. The fitted value of η for this fiber is 0.40 ± 0.05. The good agreement between theory and experiment observed in Figs. 5 and 6 provides conclusive evidence that the majority of the pump-induced phase shift in the codoped fibers is due to thermal effects, and consequently very little, if any, is due to the nonlinear effect. It also confirms that measuring the dependence of the phase shift on pump pulsewidth can differentiate between a thermal and a nonlinear origin. Note that the temperature increase of the core is small, about 7 °C for a 20-μs, 214-mW pump pulse, absorbed over 1.8 mm, where 1.7 μJ is converted to heat.

Nonradiative decay mechanisms are often associated with the presence of clusters [7], which tend to form at higher dopant concentrations. The question therefore arises as to whether the thermal effects observed in Co-doped fibers are

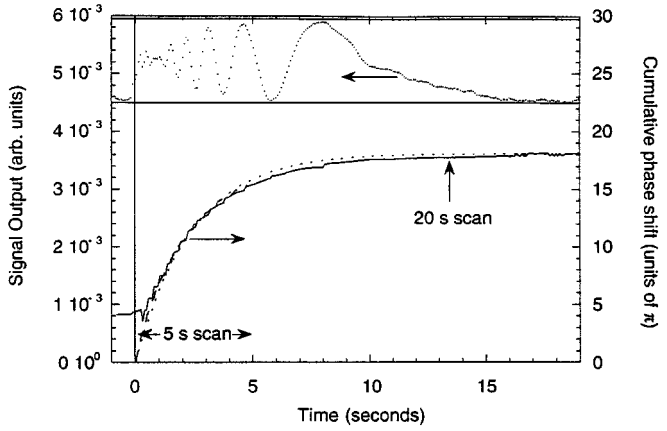

Fig. 7. Measured MZ signal output (top trace) and inferred thermal phase change (bottom solid trace) measured in the V-doped fiber after a cw pump is first turned on. The smooth dotted curve is a theoretical fit to the data.

due to electronic relaxation within ions or within clusters. We attempted to answer this question by repeating the measurement of η for fibers covering a broad range of Co^{2+} concentrations, from 8 wt ppm CoO to over 1 wt %. The inferred values of η are summarized in Table I. Within experimental errors, η is not strongly linked to concentration. Although this result is inconclusive in itself, it may indicate that Co^{2+} forms clusters at low concentration. This hypothesis is supported by the fast thermal rise time: the onset of the phase shift occurs immediately with application of the pump in Fig. 4, while other measurements involving shorter pump pulses lead to rise times as short as a few nanoseconds [8]. The fact that the observed phase shift has a largely thermal origin (see Figs. 5 and 6) suggests strongly that the radiative lifetime of Co^{2+} ions is much longer than the nonradiative lifetime, otherwise the phase shift would exhibit a measurable electronic component, [1] which we would have seen. This long radiative lifetime is consistent with the relatively large bandgaps of Co^{2+} in MgF_2 (~5,000 cm^{-1}, see Fig. 2), from which we estimate a radiative lifetime of at least 220 ns (this estimate assumes a transition oscillator strength as strong as 0.1, which is highly improbable) [1]. On the other hand, the nonradiative lifetime of a 5000-cm^{-1} transition in silica is at least in the millisecond range [9]. Thus the thermal effects due to relaxation within Co^{2+} ions cannot be the origin of the observed fast thermal phase changes. On the other hand, a rise time of a few ns is consistent with the fast nonradiative processes that typically take place within clusters.

From the energy diagram of Fig. 2 we can calculate a value of $\eta = 32\%$ for Co^{2+}-doped crystalline MgF_2. The absorption bands being generally somewhat broader in an amorphous material, the value for η is expected to be slightly higher for Co^{2+} in silica, which is consistent with the measured values (see Table I).

IV. Measurements in Vanadium-Doped Fiber

Similar studies were carried out with a low-concentration vanadium-doped silica- based fiber (see Table I). The degree of oxidation of the vanadium ions in this fiber was not unique, but included $n = 3$, 4, and 5 in unknown proportions. To match the absorption and transmission bands of vanadium in silica [5], the pump was changed to 906 nm and the signal to 1550 nm. Measurements revealed the presence of pump-induced phase modulations with a fall time that depends on pump pulsewidth, which confirmed a thermal origin.

We utilized this fiber to analyze the behavior of thermal index changes in the steady-state regime. The pump beam was blocked and unblocked for at least a full minute, and the MZ signal output monitored for several seconds after the pump was turned on. A typical signal trace, observed for an absorbed pump power of 74.4 mW, is shown in the top curve of Fig. 7. The phase shift inferred from it is plotted as the bottom solid curve. The signal oscillated back and forth between the two output ports of the MZ as its phase increased by several π over the course of a few seconds. As predicted in [2], this behavior is indicative of thermal effects. As the pump remains on, the heat input increases, and so do the core temperature and the signal phase. After around 15 s an equilibrium is reached between the rate of heat input (pumping) and the rate of heat output (convection at the cladding-air interface), and the temperature stops increasing. The dashed curve represents the theoretical growth of the index change (proportional to $1 - \exp(-t/\tau)$) [2], fitted with a time constant of 2.35 s and an absorbed pump power turned into heat of 41.5 mW. From the latter, we infer $\eta = 41.5/74.4 \sim 56\%$. From the observed steady-state phase shift of 18.4π (see Fig. 7), using [2] we can infer a fiber temperature rise of 1.6 °C. Again we conclude that the V-doped fiber we tested is a weak nonlinear material.

V. Conclusion

We have provided experimental evidence of strong thermal effects in both Co^{2+}-doped and V^{n+}-doped fibers. The measured magnitude and time constants of these effects are consistent with, and confirm the validity of, a new theoretical model. Measurements also demonstrate a new and simple method to differentiate between the nonlinear and thermal phase changes induced in a doped fiber by an optical pump, which is to identify whether the phase change depends on pump pulsewidth. The percentage of absorbed power transformed into heat was determined to be in the vicinity of 38% for cobalt and 56% for vanadium. In the case of cobalt, this figure does not appear to be dependent on concentration, yet the very short thermal rise time suggests that Co^{2+} forms clusters even at concentrations as low as 8wt ppm CoO. From these properties we conclude that these two materials, and probably many other transition metal ions in a silica-based glass, exhibit a negligible resonantly enhanced nonlinearity.

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