<table>
<thead>
<tr>
<th>Title</th>
<th>Optical bistability in Er-Yb co-doped phosphate glass microspheres at room temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Author(s)</td>
<td>Ward, Jonathan M.; O'Shea, Danny G.; Shortt, Brian J.; Nic Chormaic, Síle</td>
</tr>
<tr>
<td>Publication date</td>
<td>2007-07-20</td>
</tr>
<tr>
<td>Type of publication</td>
<td>Article (peer-reviewed)</td>
</tr>
</tbody>
</table>
| Link to publisher's version | http://link.aip.org/link/doi/10.1063/1.2753591  
http://dx.doi.org/10.1063/1.2753591  
Access to the full text of the published version may require a subscription. |
http://jap.aip.org/about/rights_and_permissions |
| Item downloaded from | http://hdl.handle.net/10468/234 |

Downloaded on 2018-12-17T18:29:58Z
Optical bistability in Er-Yb codoped phosphate glass microspheres at room temperature

Jonathan M. Ward
Department of Applied Physics and Instrumentation, Cork Institute of Technology, Bishopstown, Cork, Ireland
and Photonics Centre, Tyndall National Institute, Prospect Row, Cork, Ireland

Danny G. O’Shea
Physics Department, University College Cork, Ireland
and Photonics Centre, Tyndall National Institute, Prospect Row, Cork, Ireland

Brian J. Shortt
Department of Applied Physics and Instrumentation, Cork Institute of Technology, Bishopstown, Cork, Ireland
and Photonics Centre, Tyndall National Institute, Prospect Row, Cork, Ireland

Síle Nic Chormaic
Physics Department, University College Cork, Ireland
and Photonics Centre, Tyndall National Institute, Prospect Row, Cork, Ireland

(Received 15 February 2007; accepted 31 May 2007; published online 20 July 2007)

We experimentally demonstrate optical bistability in Er$^{3+}$-Yb$^{3+}$ phosphate glass microspheres at 295 K. Bistability is associated with both Er$^{3+}$ fluorescence and lasing behavior, and chromatic switching. The chromatic switching results from an intrinsic mechanism exploiting the thermal coupling of closely spaced energy levels, and occurs simultaneously with the intensity switching. A contrast ratio of 2.8 has been obtained for chromatic switching. The intensity switching shows ratios of 21 for 520 nm and 11 for 660 nm fluorescence emissions, and 11 for IR lasing at 1.5 μm. Concurrent with these observations, we investigate a temperature-dependent absorption of pump power, which exhibits bistable behavior. The influences of the host matrix on lasing and fluorescence mechanisms are highlighted. © 2007 American Institute of Physics. [DOI: 10.1063/1.2753591]

I. INTRODUCTION

Optical bistability (OB) in a sodium vapor was reported by Gibbs in 1976 and, since then, numerous other materials exhibiting the phenomenon have been studied, including Yb$^{3+}$ doped glasses and crystals, and semiconductors. The mechanisms responsible for nonlinearity in glasses and crystals are varied, with many requiring cryogenic temperatures (typically < 40 K) to maintain the necessary low atomic decay rates in Yb$^{3+}$ dimer and monomer systems. Alternative and more easily achievable mechanisms include photon avalanche and thermal avalanche, suggesting that a wider range of materials can exhibit OB at room temperature and above. However, no evidence of OB through these mechanisms in this temperature range has yet been observed. Bistable sensitized luminescence in Er-Yb:CsCdBr$_3$ was shown by Redmon and Rand, and, subsequently, by Ródenas et al. in a Nd-Yb codoped crystal. They also described chromatic switching in addition to the more traditional intensity switching, though both mechanisms required temperatures well below room temperature. In chromatic switching, the wavelengths of light emitted from an optically pumped sample change abruptly as a function of pump power. In contrast, for intensity switching, the output intensity at any particular wavelength changes abruptly as a function of pump power. To date, OB has also been predicted and observed in Yb$^{3+}$ doped oxide crystals, Cr-doped LiSrGaF$_6$ and LiSrAlF$_6$ crystals, Sm$^{3+}$ doped glass microspheres, and Tm$^{3+}$-Yb$^{3+}$ codoped glass. The later system exhibited multiple hysteresis loops in the fluorescence intensity at room temperature.

The interest in studying micron-sized spherical cavities stems from the potential they offer as components for experiments ranging from the very applied realization of all-optical networks to fundamental quantum optics experiments, whereby the microspheres can be used as ultrahigh Q cavities for measurements based on the principles of cavity quantum electrodynamics. Such microcavities can be either active or passive depending on the material used. For example, a sphere doped with the triply ionized rare-earth ions Er$^{3+}$ can yield fluorescence emissions ranging from UV to IR through various upconversion mechanisms due to the close proximity of the numerous energy levels in the ion. Microcavities that exhibit optical bistability are interesting for generating optical switches for all-optical computing, and miniature C-band laser sources are important for telecommunications applications. These factors have resulted in significant research focusing on the characterization of microcavities in recent years.

The concept of an Er$^{3+}$-Yb$^{3+}$ codoped glass laser was demonstrated in 1965 as a means of optimizing the Er$^{3+}$...
emission cross section while simultaneously ensuring an optimum Yb\(^{3+}\) absorption cross section\(^{15}\). This overlap alleviates the difficulty of trying to directly pump the narrow Er\(^{3+}\) absorption band. Phosphate glass has been investigated as a host matrix for rare-earth ions due to its favorable properties, such as (i) the possibility of obtaining large dopant concentrations (up to \(1.8 \times 10^{21}\) ions/cm\(^3\) for Yb\(^{3+}\), and \(~10^{19}\) ions/cm\(^3\) for Er\(^{3+}\)) compared to silicate, borate, and fluoride glasses, (ii) its large absorption band in the near-infrared region, (iii) its large emission cross section at 1.5 \(\mu\)m, and (iv) the low back energy transfer from Er\(^{3+}\) ions to Yb\(^{3+}\) ions\(^{15-17}\). The spectral characteristics are also especially beneficial for C-band lasing; the intermediate lasing level \(^{4}I_{15/2}\) has a high nonradiative relaxation rate (\(<1 \mu s\) lifetime, maximum phonon energy of 1300 cm\(^{-1}\)) to the \(^{4}I_{13/2}\) level compared with silica (maximum phonon energy of 1190 cm\(^{-1}\)), and the long lifetime of the \(^{4}I_{13/2}\) level of about 8.45 ms facilitates population inversion and high gain.\(^{12}\) The larger phonon energy of phosphate glass has a negative effect on the upconversion efficiency compared to fluoride glass (with a maximum phonon energy of 600 cm\(^{-1}\)). This, however, is counterbalanced by the large dopant concentrations and wide absorption cross section of the Yb\(^{3+}\) sensitizer. In addition, phosphate glass has better optomechanical properties compared to other glasses used for OB, such as CsCdBr\(_3\).

Here, we report on the simultaneous observation of chromatic and intensity OB in phosphate glass (Schott IOG-2) at room temperature. We present experimental results on lasing around 1550 nm and propose suitable upconversion mechanisms for the observed three color emission bands. Optical bistability previously demonstrated in passive silica\(^{8,18}\) and silicon\(^{8}\) resonators was attributed to nonlinearities arising from the Kerr effect or thermo-optic effect of the resonance line, together with high \(Q\) factors (\(Q > 10^8\)) and a tunable, narrow linewidth laser. The results presented here clearly show that IOG-2 microspheres exhibit bistable switching behavior under vastly different conditions; we use microspheres with relatively high loaded cavity \(Q\)’s typically \(1 \times 10^7\), and the pump laser has a linewidth of 1 nm and is not locked to individual cavity resonances. For clarity, our results are organized in two sections: fluorescence and lasing emissions are discussed in Sec. III, and the results of the OB measurements are discussed in Sec. IV.

II. EXPERIMENT

The IOG-2 glass used is doped with 2 wt % \(\text{Er}_2\text{O}_3\) (1.7 \(\times 10^{20}\) ions/cm\(^3\)) and codoped with 3 wt % \(\text{Yb}_2\text{O}_3\) (2.5 \(\times 10^{20}\) ions/cm\(^3\)). We study lasing and upconversion fluorescent emissions following CW pumping with a tunable 980 nm laser diode (spectral width \(~1\) nm). IOG-2 glass, with a low glass transition temperature of around 648 K,\(^{19}\) is ideal for producing microspheres with diameters of between 30 and 70–\(\mu\)m using a microwave plasma torch.\(^{20}\) A detailed description of our experimental approach has been published elsewhere.\(^{21}\) Efficient coupling of the pump into the microsphere is attained by using adiabatically tapered fibers fabricated using a direct heating technique.\(^{22}\) We use a 1–\(\mu\)m-diam, 1550 nm SMF-28 fiber with a typical transmission loss of 0.1 dB/cm. The alignment of taper and microsphere is optimized by adjusting the relative positions of the two, while maximizing the 1550 nm emissions. These lasing emissions are monitored by connecting one end of the fiber taper to an optical spectrum analyzer. During alignment we also monitor the transmission through the fiber and, typically, 10%–15% of the pump light is coupled into the microsphere. All upconversion fluorescence spectra were acquired by free space coupling into an Ocean Optics 2000 spectrometer.

III. LASING AND FLUORESCENCE IN IOG-2

In our first experiments, we changed the 980 nm pump power from 0 to 10 mW and observed a clear change in the visible emission spectra obtained, as shown in Fig. 1(a) for powers of 2.6 mW, 8.5 mW, and 9.2 mW. These results were obtained for a 50–\(\mu\)m-diam sphere and the chromatic switching behavior is clearly evident at room temperature, by the change in the ratio of the emissions at different wavelengths for the different pump powers. We note three distinct emission bands corresponding to erbium transitions at 520 nm (\(^{2}H_{11/2} \rightarrow ^{4}I_{15/2}\)), 550 nm (\(^{2}S_{3/2} \rightarrow ^{4}I_{15/2}\)), and 660 nm (\(^{4}F_{9/2} \rightarrow ^{4}I_{15/2}\)). The red emission is stronger than red emissions produced in other singly doped glasses investigated in our laboratory, such as Er:ZBLALiP and Er:ZBNA, due to the much larger Yb\(^{3+}\) absorption cross section compared to Er\(^{3+}\). One would expect the slope of the fluorescence to exhibit a simple power law dependence, \(I_{\text{emission}} \propto I_{\text{excitation}}^{a}\) where \(a\) is the number of pump photons required to produce each emit-
ted photon, thus reflecting the multiphoton nature of the upconversion process. However, this law fails in the presence of OB, as will be shown in Sec. IV. Note that, on occasion, we have also observed a very weak, but distinct, fourth emission band in the UV corresponding to an erbium transition at 740 cm$^{-1}$,23 comparable to the maximum phonon energy of 1300 cm$^{-1}$ for phosphate glasses.12 As such, only one phonon is required to bridge the energy difference between the two green levels, thereby populating the $^2\text{H}_{11/2}$ level at room temperature. The thermalization of the $^2\text{H}_{11/2}$ level by the $^4\text{S}_{3/2}$ level has a temperature-dependent effect on the ratio of the radiative emissions from these two levels as well as the excited state lifetimes.23 The multiphonon stimulated emission rate between these levels at a temperature $T$ is

$$K_{\text{mp}}(T) = K_{\text{mp}}(0) \left[ 1 - \exp \left( - \frac{\hbar \omega}{k_B T} \right) \right]^p,$$

where $k_B$ is Boltzmann’s constant, $\omega$ is the phonon frequency, and $p$ is the number of phonons required to bridge the energy gap $\Delta E$ between the levels and is given by $\Delta E/\hbar \omega$, where $\hbar \omega$ is the phonon energy. For Er-Yb codoped glasses, $K_{\text{mp}}(295 \text{ K})$ is typically of the order of $10^{11} \text{ s}^{-1}$, which is significantly higher than the value of $10^5 \text{ s}^{-1}$ reported for radiative emissions,24 indicating that the multiphonon decay is dominant. The energy difference between the $^4\text{S}_{3/2}$ level and the next lowest level $^4\text{F}_{9/2}$ requires three phonons, therefore making this level far less likely to be populated from the $^4\text{S}_{3/2}$ level.

The emissions detected from the IOG-2 microsphere, as shown in Figs. 1 and 2, are due to upconversion processes involving multiple pump laser photons and/or lattice phonons. Two upconversion mechanisms which must be considered when trying to understand the origin of the fluorescence results are excited state absorption (ESA) and energy transfer upconversion (ETU).23,25 These are shown in the energy level diagram in Fig. 3, in which we identify a number of different groups of transition processes, 1–5, that play a

![FIG. 2. (Color online) Lasing spectrum and whispering gallery mode structure for a 50-μm-diam IOG-2 microsphere (same as for Fig. 1).](image1)

![FIG. 3. (Color online) Energy level diagram and fluorescence mechanisms with radiative (solid lines) and nonradiative transitions (wiggly lines). (1) Upconversion based on GSA and ESA in ion A only; (2) radiative and nonradiative decays; (3) and (4) energy transfer processes from ion A to ion B populating the $^4\text{F}_{9/2}$ level in ion A; (5) GSA and ESA in ion B; (CR) cross relaxation; (ET) energy Transfer; (GSA) ground state absorption; (ESA) excited state absorption.](image2)
role in the generation of the emission spectra. The combination of relatively high cavity quality factor (typically $1 \times 10^5$) and strongly localized electromagnetic field in the form of a whispering gallery mode (mode volume $\sim 3000 \mu m^3$) serves to significantly enhance the probability that an excited ion will absorb further pump photons.

Transition groups $\oplus$ and $\ominus$ in Fig. 3 are associated with the ground state (GSA) and excited state absorptions in a single erbium ion. As mentioned, there is a resonant energy transfer (ET) from the Yb$^{3+}$ sensitizer ($^2F_{5/2} \rightarrow ^2F_{7/2}$) to the Er$^{3+}$ ion ($^4I_{15/2} \rightarrow ^4I_{11/2}$) followed by 980 nm ESA from the $^4I_{11/2}$ level to the $^2F_{7/2}$ level indicated in group $\oplus$. Transition group $\ominus$ deals with the radiative and nonradiative decay processes for a single erbium ion. For example, rapid, nonradiative relaxation from $^4I_{11/2}$ to $^4I_{13/2}$ is possible and falls within this group. In spite of a large energy mismatch of about 1450 cm$^{-1}$ for the $^4I_{13/2} \rightarrow ^4F_{g/2}$ transition, the long lifetime of the $^4I_{13/2}$ state and associated large population ensures that the ETU mechanism is adequately efficient.$^{23,26}$ Due to the close spacing of the $^2F_{7/2}$ and $^4S_{3/2}$ levels, the population of $^2F_{7/2}$ readily decays nonradiatively to the $^4S_{3/2}$ level, whereby the thermal mechanism described previously populates the $^2H_{11/2}$ level. Finally, a second ESA from the $^4S_{3/2}$ level up to the $^2G_{7/2}$ level is followed by nonradiative relaxation down to the $^2H_{9/2}$ level and the subsequent radiative decay to the ground state generates a photon at 410 nm (violet).

At the high concentrations of Er$^{3+}$ and Yb$^{3+}$ in this work the ion separation reaches a critically small radius of $\sim 3$ nm for Er$^{3+}$ ions and $\sim 2$ nm for Yb$^{3+}$ ions. This is close to the value of 2.12 nm for Yb$^{3+}$-Yb$^{3+}$ ET’s and an estimated 1.5–2.0 nm for Yb$^{3+}$-Er$^{3+}$ ET’s as determined from the Förster-Dexter theory,$^{27,28}$ dramatically enhancing the probability of Yb$^{3+}$-Yb$^{3+}$, Yb$^{3+}$-Er$^{3+}$, and, presumably, Er$^{3+}$-Er$^{3+}$ energy transfer processes. The critical radius $R_{cr}$ is determined by the overlap of the emission and absorption cross sections and is given by

$$R_{cr}^2 = \frac{3c\tau_r}{8\pi n^2} \int \sigma_{ems}(\lambda)\sigma_{abs}(\lambda)d\lambda,$$

where $c$ is the velocity of the photons, $\tau_r = 1.4$ ms is the fluorescence decay time of the unperturbed sensitizer, $n$ is the refractive index, $\sigma_{ems}$ is the emission cross section, and $\sigma_{abs}$ is the absorption cross section. The emission and absorption cross sections are shown in Fig. 4, and are determined from measurements with a bulk sample of IOG-2. The ion $s$ stands for the sensitizer, i.e., the Yb$^{3+}$ ions, and the ion $x$ stands for either the sensitizer or the Er$^{3+}$ acceptor ions. For nonradiative dipole-dipole interactions the energy transfer rate rapidly increases according to the inverse of the ion separation to the sixth power.

A further group $\otimes$ transition deals with red emissions from a single erbium ion. However, the strength of the observed red emission cannot be wholly explained by multiphonon relaxation from the $^4S_{3/2}$ level to the $^4F_{g/2}$ level, due to the low relaxation rate. Notwithstanding the ESA process already mentioned, two ETU cross-relaxation channels can explain the strength of the red emission relative to the green emissions and the associated processes are indicated by transition groups $\oplus$ and $\ominus$ in Fig. 3. The first ETU is via $4I_{11/2}(B) + 4I_{13/2}(A) \rightarrow 4I_{15/2}(B) + 4F_{g/2}(A)$ and the second channel is via $^2H_{11/2}(B) + ^4I_{11/2}(A) \rightarrow 4F_{g/2}(B) + 4F_{g/2}(A)$, where $A$ and $B$ denote the two erbium ions involved. Therefore, ions are removed from the green levels and transferred to the red $^4F_{g/2}$ level. The two possible cross-relaxation processes feeding the $^4F_{g/2}$ level deplete the intermediate $^4I_{11/2}$ level and the metastable $^4I_{13/2}$ level, thereby placing the $1.5 \mu m$ emission in competition with the red emission and the other upconversion processes. We find that the power of the red emission is, typically, twice as high in microspheres that exhibit no lasing (due to excessive inhomogeneities in the cavity) compared to those that exhibit lasing.

IV. RESULTS AND DISCUSSION

A. Intensity switching

In order to study the optical bistability of the microspheres we measured the emission intensity as a function of launched pump power for a single sphere at three different emission wavelengths: 520 nm (green), 660 nm (red), and 1550 nm (IR). The pump power was increased from 0 to 10 mW and back to 0, while recording the fluorescence emission intensities [Fig. 5(a)]. These measurements were taken simultaneously to the transmitted pump power shown in Fig. 1(b). As the launched pump power was increased the emission intensities remained almost constant until a critical power of 8.5 mW was reached [cf. Fig. 5(a)], beyond which a sudden and dramatic rise in emission intensity was observed. Increasing the pump power beyond the critical point caused the emission to level out once more. A subsequent reduction in pump power clearly demonstrates hysteretic behavior and a wide bistable region, where the emission can have two intensity values depending on the history of the input power. The sudden jumps (or intensity switching) between the higher and lower branches of the hysteresis loops are characteristic of the optical bistability of the spheres. A bistable response was also observed for the lasing emission in Fig. 5(b) for the same sphere, but in a slightly different
and 11 for the IR as determined from Fig. 5. The violet emissions.

As referred to earlier, the strong temperature dependence
is the total spontaneous emission rate,

\[ I_{\text{sp}} = \frac{r g S_{\text{sp}} \hbar \omega_S}{r g S_{\text{sp}} \hbar \omega_S} \exp \left( \frac{\Delta E}{k_B T} \right), \]

where \( I \) is the integrated emission intensity for a particular
level, \( r \) is the total spontaneous emission rate, \( g \) is the \((2J + 1)\) multiplicity (or degeneracy) of each manifold,
\( \hbar \omega_H(\hbar \omega_S) \) is the energy of level \(^2\!H_{1/2}(^4S_{3/2})\), and \( \Delta E \) is the
energy separation between the levels. According to Eq. (3),
as the temperature is increased the \(^2\!H_{1/2}\) level is more
efficiently populated and an increasingly larger fraction of the
\(^4S_{3/2}\) population is rapidly promoted to this upper level and,
consequently, the ratio of the emissions from the two states
inverts so that the \(^2\!H_{1/2}\) emission becomes stronger. This
chromatic switching can yield intensity ratios of up to 2.8 for
the integrated power from the 520 nm (\(^2\!H_{1/2}\)) and 550 nm
\(^4S_{3/2}\) emissions (data not shown). From Eq. (3) this
indicates a temperature of 642 K, just below the glass transition
value of 648 K. This temperature seems exceptionally high,
although there was no evidence of thermal stresses, fractur-
ing of the glass or other defects in the microsphere during
these measurements. However, it is important to emphasize
that the temperature calculated using this method does not
represent the temperature of the entire sphere, but rather the
temperature of the mode volume. Heat dissipation from this
region through the remainder of the material would account
for no evident thermal stress on the sphere itself, which is
likely to be at a much lower temperature.

C. Temperature dependence of optical bistability

Previously reported mechanisms for OB in Tm-Yb-
doped BaY2F8 crystals have suggested that photon avalanche
may be a possible mediator, while for silica microspheres the
Kerr effect led to OB at 2 K. Both these mechanisms are
temperature independent. However, other mechanisms such
as the thermo-optic effect, nonlinear upconversion and en-
tergy transfer rates, and thermal avalanche are tempera-
ture dependent. In order to gain a further understanding on
the mechanisms involved, the temperature dependence of the
OB was examined by placing a platinum heater and thermo-
couple close to the microsphere and heating it to around 345
K. The pump power transmitted past the taper-sphere junc-
tion was recorded at the same time as the microsphere emis-
sions, while cycling the pump power from low to high and
back again as shown in Fig. 6. Comparison of the plots taken
at room temperature and at 345 K shows that an increase in
external temperature causes the upper knee at 17 mW input
power to shift down to 13 mW, while the lower knee at 7
mW only shifts slightly to the right, thereby shortening the
 bistable region. The pump power was cycled at a slow rate of
~1 mW/min due to the thermal response time of the micro-
sphere. The bistable microsphere emissions are essentially
the same as those shown in Fig. 5 except for the different
switching positions, and the results shown in Fig. 6 imply
that the bistable behavior is a function of temperature.

D. Possible optical bistability mechanisms

In principle, a number of processes may be responsible
for the observation of optical bistability, depending on
whether the observed effect is temperature dependent or
independent. The measurements shown in Fig. 6 indicate
clearly that the bistable behavior exhibited by our micro-
spheres is temperature dependent, thereby permitting us to
exclude temperature independent processes. Temperature-

![Fig. 5. (Color online) Intensity bistability for green \(^2\!H_{1/2}\) state, red \(^4F_{9/2}\)
state, and 1.5 \(\mu\)m lasing from the \(^3\!F_{3/2}\) state for a 50-\(\mu\)m-diam sphere. The
switching positions for the green and red emissions in (a) differ from the
1.5 \(\mu\)m lasing emission in (b) due to a different setup with a poorer taper-
sphere coupling. The corresponding spectra for the visible fluorescence are
shown in Fig. 1(a).]
dependent mechanisms that may be responsible include material effects such as (i) strong Yb$^{3+}$-Yb$^{3+}$ coupling, i.e., non-linear energy transfer,\(^\text{32}\) (ii) non-linear upconversion rates,\(^\text{33}\) and (iii) thermal avalanche,\(^\text{2}\) in addition to cavity effects such as (iv) dispersive bistability mediated by the thermo-optic effect.\(^\text{33,34}\)

Guillot-Nöel\(^\text{et al.}\)\(^\text{32}\) have described a mechanism that could be responsible for bistability in the regime of strong Yb$^{3+}$-Yb$^{3+}$ coupling, in which case cooperative luminescence would be expected. In order to be appreciable, the distance between the ions would need to be of the order of several Å, i.e., significantly smaller than for IOG-2 (21 Å) and, therefore, this effect is unlikely to play a key role. However, if it is present, the luminescence would likely be very weak compared to the single ion Er$^{3+}$ transitions. It is reasonable to assume the back transfer rate is negligible due to the high phonon energy of the host lattice, and is, therefore, unlikely to be the source of nonlinearity in our measurements.

Another possible explanation includes a non-linear upconversion rate either for Yb$^{3+}$-Yb$^{3+}$, Yb$^{3+}$-Er$^{3+}$, or Er$^{3+}$-Er$^{3+}$ energy transfers.\(^\text{33}\) This has been observed in high concentration Er$^{3+}$ doped fibers, where the nonlinearity is dependent on population inversion of the lasing levels, and the signal and emission rates. Temperature-dependent effects in the upconversion fluorescence in Er-YbGa$_2$S$_3$:La$_2$O$_3$ chalcogenide glass and germanosilicate optical fibers have been attributed to an exponential increase in the Yb$^{3+}$ absorption cross section elsewhere.\(^\text{35}\) However, there have been no reports of bistability relying on these mechanisms.

Thermal avalanche was used to explain bistability in Yb$^{3+}$-doped bromide lattices by Gamelin\(^\text{et al.}\)\(^\text{2}\) at cryogenic temperatures. This theory relies on non-linear absorption in the Yb$^{3+}$ ions with increasing temperature and predicts bistable power absorbance in the microsphere as a function of pump power in the taper, similar to that shown in Fig. 6. As phonons are released into the lattice from Yb$^{3+}$ excited and ground states the temperature increases, thereby increasing absorbance and leading to a further increase in temperature. This cyclic process causes a thermal avalanche for high enough pump power. In order to determine whether thermal avalanche is truly responsible, it would be necessary to perform measurements of the dependence of the Yb$^{3+}$ absorption coefficient and to ascertain whether it is a non-linear function of internal microsphere temperature above 295 K. However, the results presented in Lei\(^\text{et al.}\)\(^\text{36}\) for different Yb$^{3+}$-doped phosphate glasses do not show a suitable non-linear absorption coefficient necessary for thermal avalanche. This suggests that thermal avalanche theory is also unsuitable to describe the behavior of IOG-2.

We suggest that dispersive bistability—a mechanism commonly used to explain bistability in Fabry-Pérot etalons—can predict our results. The general theory states that as the pump laser frequency is scanned across a high-$Q$ cavity resonance, the cavity intensity rapidly rises, and when the pump frequency moves away from the cavity resonance the cavity intensity rapidly falls. In addition, this description is complicated by the fact that the frequency of the cavity resonance scales approximately linearly with the cavity intensity, leading to a bistable response. In our case, the cavity resonance could be shifted by a temperature-dependent refractive index—the thermo-optic effect—which has a value of \(~10^{-6}/\text{K}\) in phosphate glass.\(^\text{20}\) We find that in order to observe bistability the current to the pump laser, and, hence, the pump frequency, need to be adjusted to a precise setting for each sphere. The corollary of this adjustment is the positioning of the laser frequency near a cavity resonance. For the experimental conditions here, a threshold power of about 100 $\mu$W in the cavity mode is enough to cause switching—a value which is well below our estimated 10%–15% of pump power coupled into the sphere. Firm evidence of this effect would be possible by probing individual cavity resonances with a narrow linewidth, 980 nm external cavity diode laser, while recording the power transmitted past the taper-sphere coupling junction as described by Rokhsari\(^\text{et al.}\)\(^\text{18}\).

V. CONCLUSIONS

In conclusion, we have demonstrated a multiwavelength, upconversion, microsphere light source exhibiting optical bistability and we have identified the Er$^{3+}$ transitions and fluorescence mechanisms involved. Factors affecting the dynamics of visible fluorescence and C-band lasing emission have been examined and show that the thermal properties of IOG-2 glass play an important role in the microsphere performance. In particular, the high loss of pump power to the glass as heat, in conjunction with the low thermal conductivity, has a pronounced effect on the green emission from levels $^2\!H_{11/2}$ and $^4S_{3/2}$. Our calculations show that the close proximity of the ions in our glass greatly enhances the probability of sensitizer-sensitizer and sensitizer-acceptor energy transfers.

We have also reported on the simultaneous observation of chromatic and intensity OB in phosphate glass (Schott IOG-2) at room temperature. These results show that there are two possible temperatures in the bistable region and it is also possible to have two emission intensities for the same excitation power. Chromatic bistability is dependent on the
presence of intensity bistability due to the energy coupling between the green emitting levels \( ^2H_{11/2} \) and \( ^4S_{3/2} \). Therefore the switching positions are the same for both types of bistability. The OB shows high contrast switching ratios. The intensity switching shows ratios of 21 for the green, 11 for the red fluorescence emissions, and 11 for the IR lasing, while the chromatic switching ratios \( I(\Delta H_{11/2})/I(\Delta S_{3/2}) \) are as high as 2.8.

We have found that the switching position is dependent on the microsphere temperature, thereby eliminating intensity-dependent mechanisms such as photon avalanche and the Kerr effect. Our observations may be tentatively explained in terms of dispersive bistability, where the temperature-dependent refractive index of phosphate glass causes the resonant cavity mode and the laser mode to behave nonlinearly, yielding a bistable response. Several other possible mechanisms (strong \( \text{Yb}^{3+}-\text{Yb}^{3+} \) coupling, nonlinear upconversion rates, and thermal avalanche) were examined; however, all are considered unfavorable under our experimental conditions.

Microcavity resonators offer substantial miniaturization, greatly reduced power for switching, and allow for all emissions to be easily fiber coupled. In addition, the improved optomechanical properties of IOG-2 compared to other glasses used for OB, such as \( \text{CsCdBr}_3 \), makes this glass appealing for all-optical logic elements in optical engineering applications.

ACKNOWLEDGMENTS

This work was funded by Science Foundation Ireland under Grant No. 02/IN1/128. The authors gratefully acknowledge P. Féron and L. Ghisa from ENSSAT for providing the IOG-2 microspheres. D.O. S. acknowledges support from the Irish Research Council for Science, Engineering and Technology through the Embark Initiative RS/2005/156.

15IOG-2 phosphate laser glass specification sheet, Schott Glass Technolo-gies, 400 York Ave., Duryea, PA 18642, USA.