Reprinted from Applied Optics, Vol. 27 page 3586, September 1, 1988

Thermal focusing effects on the supercontinuum

Jamal T. Manassah, P. L. Baldeck, and R. R. Alfano

CUNY-City College, Department of Electrical Engineering, New York, New York 10031.
Received 16 March 1988.
0003-6935/88/173586-02$02.00/0.

It has long been recognized[1] that the propagation of a laser beam in a material produces local heating in the beam vicinity and that the temperature gradient in the material induces a transverse gradient of the refractive index which leads to a lensing effect. We have recently shown[2] that the phase shape and spectral distribution of a pulse propagating in a parabolic graded-index material differ significantly from conventional self-phase modulation[3] results. This temperature gradient can in the case of supercontinuum generation with a high repetition rate produce significant variations in the spectral extent and shape.[4] Properly controlled, for example, by using a cw heating beam, it is also possible to use this effect in optical fibers, lead glass, and certain semiconductors where $dn/dT > 0$ (Refs. 5–7) to control the sign of the pulse phase such as to reverse the red leading the blue in the supercontinuum and possibly to compress pulses within $\chi^{(3)}$ materials without the need for external gratings or prisms. In this Letter, we find the normalized beam diameter, the pulse phase and the supercontinuum spectral shape in the presence of such temperature gradients.

Gordon *et al.*[1] results can essentially be summarized that due to heating the index of refraction in the material is given by

$$n = n_0\left[1 + \frac{\delta'}{r_H^2} r^2\right], \tag{1}$$

where r_H is the heating beam spot size, n_0 is the material linear index of refraction, and

$$\delta' = -\frac{0.12Pb}{n_0\kappa\pi}\left(\frac{dn}{dT}\right)\frac{8Dt}{r_H^2 + 8Dt}, \tag{2}$$

where

$$D = \frac{\kappa}{\rho C_p}, \tag{3}$$

P is the heating laser power (in watts), b is the fractional power dissipation in the medium per centimeter, κ is the thermal conductivity (cal/cm s K), ρ is the density (g/cm^3), C_p is the specific heat (cal/g K), and dn/dT measures the change in the material index of refraction for a change in its temperature.

A pulse whose envelope is given by

$$\epsilon(r,0,u) = \epsilon_0 \exp\left(-\frac{r^2}{a^2}\right)\exp\left(-\frac{u^2}{2\tau^2}\right) \tag{4}$$

at the entrance of $\chi^{(3)}$. Nonlinear material, where $u = z/v_g - t$, v_g is the group velocity, a is the initial beam radius, τ is the pulse duration, r is the cylindrical radius, and ϵ_0 is the magnitude of the pulse, will develop through the nonlinear material to give an envelope $\epsilon(r,z,u)$ at the space–time point (r,z,u).[2] The functional form of $\epsilon(r,z,u)$ is given by

$$\epsilon(r,z,u) = \frac{\tilde{\epsilon}_0}{\omega(z,u)} \exp\left[-\frac{r^2}{a^2\omega^2(z,u)} - i\frac{k}{2}\rho(z,u)r^2 + ik\alpha(z,u)\right], \tag{5}$$

where $\tilde{\epsilon}_0 = \epsilon_0 \exp(-u^2/2\tau^2)$ and the functions ω,ρ,α are given for focusing materials (i.e., $dn/dT > 0$) by

$$\omega = [\beta\cos(\gamma z) + \delta]^{1/2}, \tag{6}$$

$$\rho = -\frac{1}{2}\frac{\beta\gamma\sin(\gamma z)}{[\beta\cos(\gamma z) + \delta]}, \tag{7}$$

$$k\alpha = \frac{ka^2(B - C)}{2[B - 2C]^{1/2}} \arctan\left[\left(\frac{B - 2C}{A}\right)^{1/2}\tan(A^{1/2}z)\right], \tag{8}$$

where $\gamma = 2[2n_0|\delta'|/r_H^2]^{1/2} = 2A^{1/2}$, $\beta = (2C - B + A)/2A$, $\delta = (A - 2C + B)/2A$, and

$$B = \frac{4}{a^4k^2} = \frac{1}{(\text{Rayleigh length})^2}, \tag{9}$$

$$C = \frac{n_2\tilde{\epsilon}_0^2}{n_0a^2}. \tag{10}$$

If we use the critical field ϵ_c for the medium, i.e., the field for which the self-focusing distance is equal to infinity, C can be written as

$$C = \frac{B}{2}p\exp\left(-\frac{u^2}{\tau^2}\right), \tag{11}$$

where

$$p = \frac{\epsilon_0^2}{\epsilon_c^2} \qquad \epsilon_c^2 = \frac{2n_0}{a^2k^2n_2}, \tag{12}$$

physically p represents the power of the incoming pulse in units of the critical power[8] of the nonlinear medium. The main features of the solutions[6–8] are as follows:

(1) The normalized beam diameter is a periodic function in z. The wavelength of this periodicity is proportional to $|\delta'|^{-1/2}$. In Fig. 1, ω is plotted for selected values of $|\delta'|$.

(2) The longitudinal phase, for $u = 0$, as function of z mostly increases by steps at z locations corresponding to the periodical positions of the minimum beam diameter. As a result this phase is not linear in z as the conventional self-phase modulation theory phase. Furthermore, its magnitude can be much larger. In Fig. 2, this phase is plotted for different values of the δ' parameter.

(3) The time-dependent portion of the longitudinal phase may have the reverse sign than that of conventional SPM. Physically, this result leads to the reverse of the red leading the blue in the supercontinuum. Furthermore, as the pulse peak magnitude increases and tends to the critical field of the nonlinear medium, the phase width decreases significantly. Therefore, for ω close to its maximum, only a short period

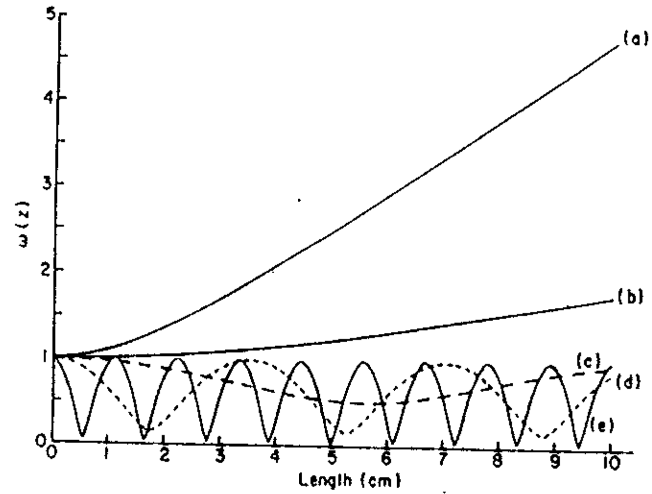

Fig. 1. Normalized probe beam diameter as a function of material thickness: (a) $p = 0, |\delta'| = 0$; (b) $p = 0.9, |\delta'| = 0$; (c) $p = 0.9, |\delta'| = 2.5 \times 10^{-3}$; (d) $p = 0.9, |\delta'| = 7.8 \times 10^{-3}$; (e) $p = 0.9, |\delta'| = 2.5 \times 10^{-2}$.

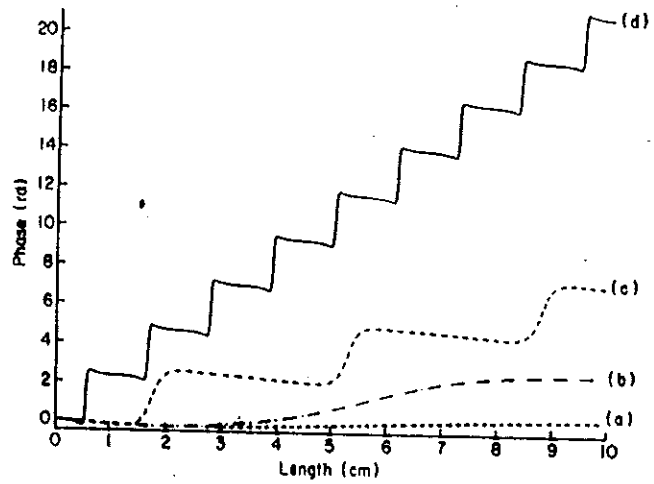

Fig. 2. Longitudinal probe phase at $u = 0$ as a function of the material thickness. $p = 0.9$. (a) $|\delta'| = 0$, (b) $|\delta'| = 2.5 \times 10^{-3}$, (c) $|\delta'| = 7.8 \times 10^{-3}$, (d) $|\delta'| = 2.5 \times 10^{-2}$.

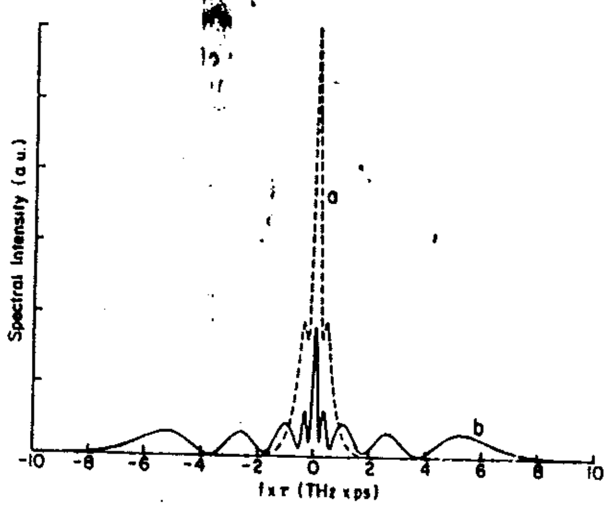

Fig. 3. Probe spectral distribution for $r = 0, z = 10$ cm, and $p = 0.9$: (a) $|\delta'| = 2.5 \times 10^{-3}$; (b) $|\delta'| = 2.5 \times 10^{-2}$.

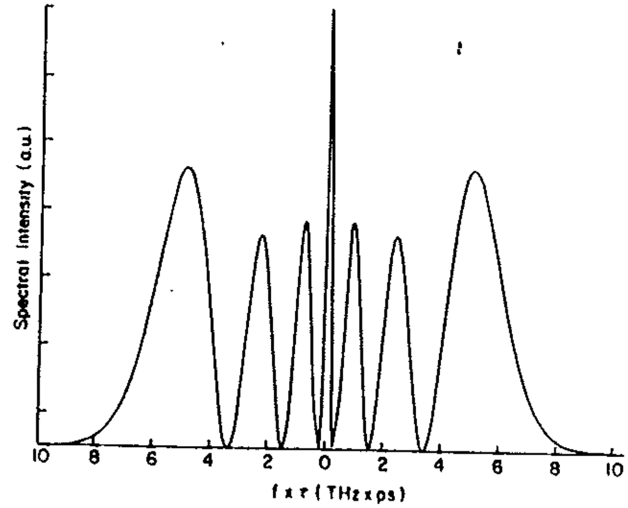

Fig. 4. Probe spectral distribution for $r = 0, z = 9.44$ cm, $p = 0.9$, and $|\delta'| = 2.5 \times 10^{-2}$.

over the pulse duration is modulated. This portion increases as ω approaches its minimum.

In Fig. 3, the spectral intensity is plotted for the same length z but for different δ' parameters. For larger δ' the spectral extent is larger.

In Fig. 4, the spectral intensity is plotted for the same δ' as of the curve in Fig. 3(*b*) but for a slightly different sample length. As can be observed the spectral extent does not significantly change with a small variation in z. However, the spectral shape can be dramatically altered. Actually, the two lengths chosen correspond to maximum and minimum positions of the normalized beam diameter.

Summarizing, we have shown in this Letter that by heating the path of a probe pulse by a heating beam (or alternately through the high repetition rate of the probe beam), it is possible to waveguide the probe pulse and alter significantly its spectral intensity distribution. Uncontrolled, this heating phenomenon can lead to random characteristics in supercontinuum generation. Controlled, it may find a number of interesting applications.

We gratefully acknowledge the partial support received from Hamamatsu Photonics K.K.

References

1. J. P. Gordon, R. C. C. Leite, R. S. Moore, S. P. S. Porto, and J. R. Whinnery "Long-Transient Effects in Lasers with Inserted Liquid Samples," J. Appl. Phys. **36**, 3 (1965).
2. J. T. Manassah, P. L. Baldeck, and R. R. Alfano "Self-Focusing and Self-Phase Modulation in a Parabolic Graded-Index Optical Fiber," Opt. Lett **13**, 589 (1988).
3. R. R. Alfano and S. L. Shapiro "Observation of Self-Phase Modulation and Small Scale Filaments in Crystals and Glasses," Phys. Rev. Lett. **24**, 595 (1970).
4. R. R. Alfano and S. L. Shapiro, "Explanation of a Transient Raman Gain Anomaly," Phys. Rev. A **2**, 2376 (1970).
5. G. B. Morey, "Properties of Glass," in *International Critical Tables, Vol. 2* (McGraw-Hill, New York, 1933).
6. F. W. Dabby and J. R. Whinnery, "Thermal Self-Focusing of Laser Beams in Lead Glasses," Appl. Phys. Lett. **13**, 284 (1968).
7. B. O. Seraphin and H. E. Bennett, in *Semiconductors and Semimetals*, R. K. Willardson and A. C. Beer, Eds. (Academic, New York, 1967), Vol. 3, p. 499.
8. P. L. Kelley, "Self-Focusing of Optical Beams," Phys. Rev. Lett. **15**, 1085 (1965).