Over 4000 nm Bandwidth of Mid-IR Supercontinuum Generation in sub-centimeter Segments of Highly Nonlinear Tellurite PCFs

P. Domachuk[1], N. A.Wolchover[2], M. Cronin-Golomb[1], A. Wang[3], A. K. George[3], C.M.B. Cordeiro*[3], J.C. Knight[3], F. G. Omenetto[1,2]

[1]Department of Biomedical Engineering, [2]Dept. of Physics, Tufts University, 4 Colby Street, Medford, MA 02155
[3]Centre for Photonics and Photonic Materials, University of Bath, Bath, UK

Abstract: We report broad bandwidth, mid-IR supercontinuum generation using a sub-cm (8 mm) length of highly nonlinear tellurite microstructured photonic crystal fiber (PCF). We pump the fiber at telecommunication wavelengths by using 1550 nm, 100 fs pulses of energy E=1.9 nJ. When coupled in the PCF, these pulses result in a supercontinuum (SC) bandwidth of 4080 nm extending from 789 to 4870 nm measured at 20 dBm below the peak spectral power. This bandwidth is comparable or in excess of previously reported spectra for other nonlinear glass fiber formulations despite the significantly shorter fiber length. In addition, besides offering a convenient pump wavelength, short fiber lengths enable smoother SC spectra, lower dispersion, and reduced material absorption at longer wavelengths making the use of this PCF particularly interesting.

OCIS codes: (190.0190) Nonlinear Optics; (320.0320) Ultrafast optics; (060.5530) Pulse propagation and solitons; (060.4370) Nonlinear optics, fibers; (230.6080) Sources.

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1. Introduction

Mid-infrared (mid-IR) photonics is seeing an increasing number of applications across a variety of disciplines. In astronomy, the mid-infrared wavelength ranges are being investigated and, as such, the need for instrumentation and practical test sources within that range are required [1,2]. Mid-IR spectroscopy is also a versatile technology with applications devoted to the study and detection of various biological species such as the derivation of protein structures [3,4]. These applications require an optical source of sufficient brightness whose wavelength range extends into the mid-IR where several overtones of relevant chemical bonds are present for spectral fingerprinting of organic compounds. Laser sources, while bright and coherent, have very limited bandwidth. Other sources, such as thermal sources, have very high bandwidths but low coherence and low brightness. Fiber generated supercontinuum (SC) light provides a useful balance of brightness, coherence and bandwidth making it an appealing optical source for investigations in this spectral region.

SC generation in photonic crystal fibers (PCFs) [5,6] is the creation of very broadband optical radiation due to the nonlinear interaction of a short optical pulse (typically tens to hundreds of fs, although longer ps pulses have been used) with the waveguide in which it is guided. The nonlinear processes responsible are varied and have been the subject of extensive investigation [5,6]. PCFs are particularly attractive candidates for SC generation (and studies of nonlinear physics in general) due to enhanced waveguide nonlinearity, typically obtained both by strongly confining a guided electromagnetic mode which then enhances the optical interaction with the fiber material [5] (albeit not unique to PCFs [7]) and by the possibility of fabricating them from a single material constituent that has high intrinsic nonlinearity such as chalcogenide [8], tellurite [9], and lead silicate [10] glasses. Generally, SC generation is achieved after propagation of the pump pulse through moderate lengths of fiber, that range anywhere from some centimeters to a few meters. However, SC generation can be obtained in significantly shorter waveguides (sub-cm) if their nonlinearity is sufficiently high in, for example, SF6 glass [10]. Importantly, shorter propagation lengths allow control over the progress of SC generation by defining the physical regime of transformation of the propagating pulse. Shorter lengths, expectedly, result in a SC generation process that is mainly driven by self-phase modulation (SPM). This was previously shown to generate smooth spectral output with a bandwidth over 2000 nm covering the near-IR [10] and was explored numerically to ensure that the spectral smoothness of the supercontinuum was not due to instrumental averaging [11] as one might be inclined to believe. The use of short fiber lengths provides additional practical advantages: specialty glasses that have high losses can be adopted since they will be mitigated in short lengths. Further, short PCFs are well suited for practical devices because of cost of exotic highly nonlinear fiber materials. Additionally, we design the PCF to be pumped at telecommunications wavelengths (1550 nm) unlike other glass formulations for mid-IR SC generation [12] adding to the practicality of this design.

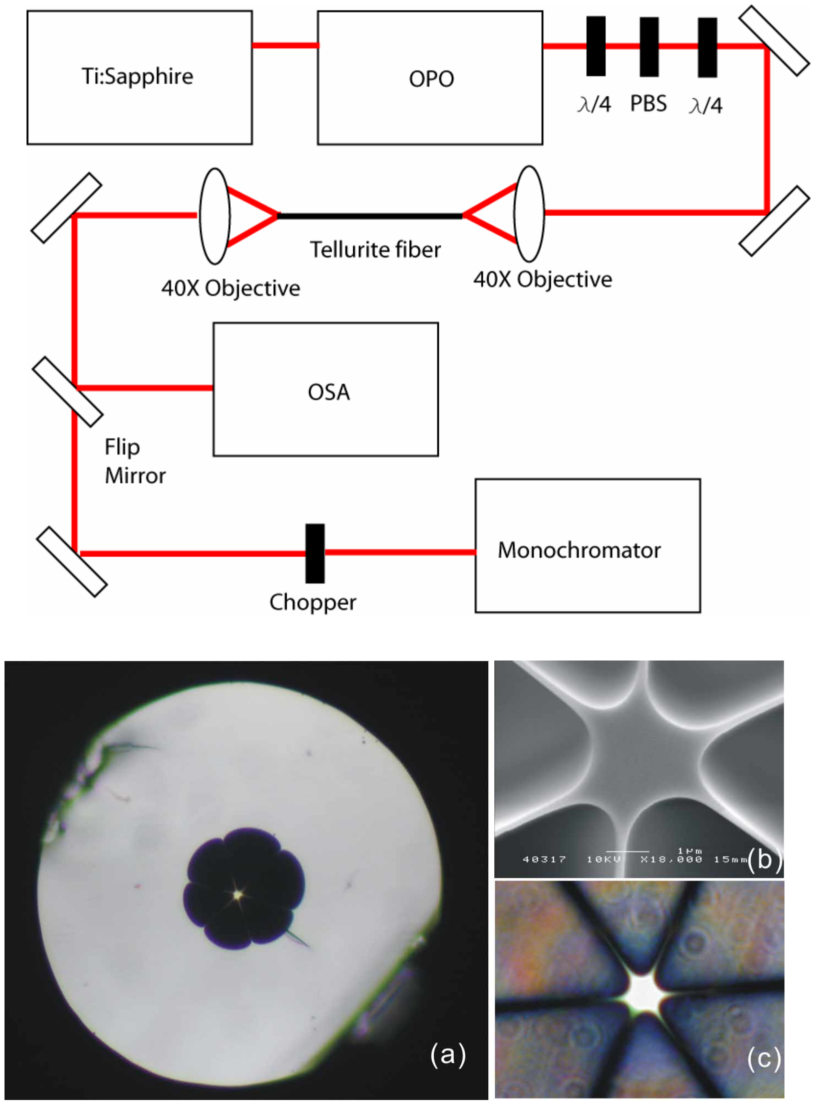

Fig. 1. (top) A schematic of the experimental arrangement used to generate and deliver fs pump pulses to the tellurite PCF for SC generation. (bottom) The cross sectional profile of the tellurite PCF in electron (b) and optical microscopy (a, c). Scale bar in (b) is 1µm.

In this paper, we demonstrate the use of a tellurite glass based PCF to realize a compact, spectrally smooth SC source extending into the mid-IR from 789 to 4870 nm. SC generation occurs in a sub-cm (8 mm) length of this PCF [13]. The combination of fiber microstructure and highly nonlinear glass provides enhanced optical nonlinearity responsible for SC output after only 8 mm of pulse propagation. The use of very short, highly nonlinear PCFs mitigates the relatively high loss of the tellurite glass and the fiber design, with a zero dispersion wavelength (ZDW) of 1380 nm, allows 1550 nm pulses to generate the SC, enabling the use of common telecommunications hardware for generating mid-IR SC.

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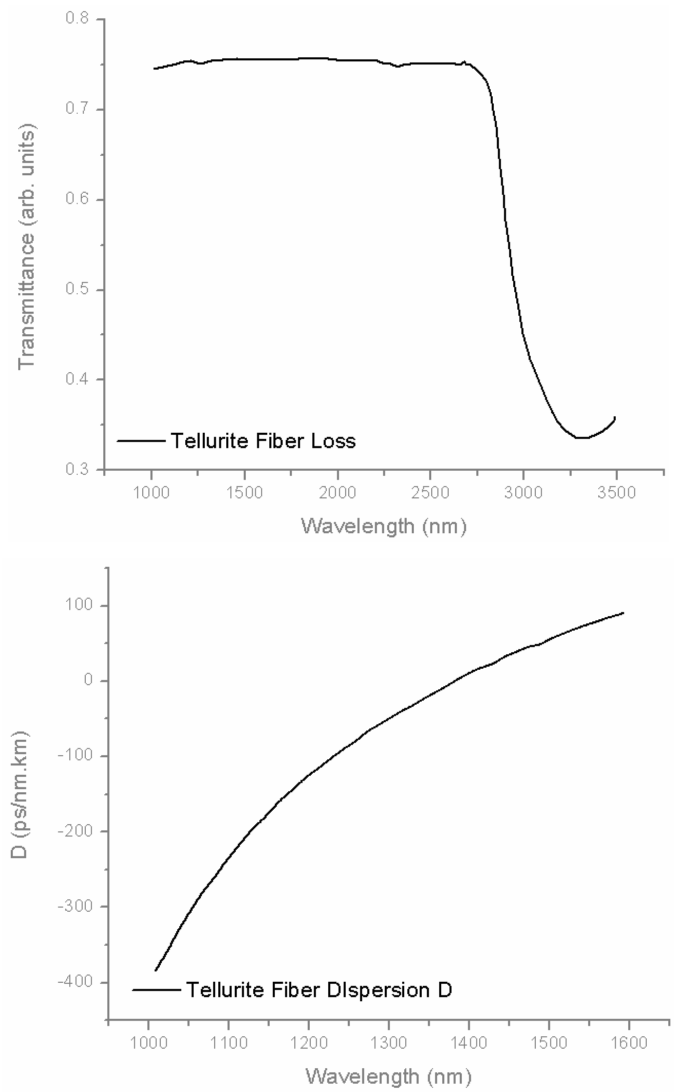

Fig. 2. (top) Transmittance of a 3 mm billet of bulk tellurite glass. The resulting fiber has a minimum of 1.8 dBm^{-1} loss at 1420 nm which increases to 8 dBm^{-1} at 1750 nm (bottom) Dispersion curve of the tellurite PCF. The zero dispersion wavelength is 1380 nm.

2. Fiber design

SC generation depends strongly upon the optical properties imposed by the photonic crystal fiber geometry and the bulk linear and nonlinear optical properties of the material used. The microstructured tellurite fiber used here is designed to have a very high nonlinear waveguide parameter γ [6] through both the high linear refractive index (resulting in strong modal field confinement in the fiber core) and through the material nonlinearity. The combined material and waveguide dispersions result in a fiber with a zero-dispersion wavelength measured to be located at 1380 nm (Fig. 2). It follows that pumping at wavelengths of 1550 nm occurs well into the anomalous dispersion regime.

Figure 1 shows images of the tellurite fiber face which consist of an electron microscope and optical image, as well as an optical micrograph that illustrates the guided light distribution in the core. The fiber microstructure is a “wagon wheel” design; a fiber of 120 µm outside

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diameter surrounds a microstructure that consists of six very fine filaments 16 μm long and 120 nm wide that support a 2.5 μm diameter core. The fiber preform was fabricated using an extrusion process from a bulk tellurite glass billet with stoichiometry $75TeO_2$ - 12ZnO - 5PbO – $3PbF_2$ – $5Nb_2O_5$, a similar formulation and identical method to that presented in earlier work [12]. The preform was jacketed in an extruded hollow tube made in the same fashion and drawn down to its final dimensions mentioned above.

Figure 2 shows the optical properties of the bulk tellurite glass bulk and of the PCF used here. The linear refractive index of tellurite glass is n = 2.0. The transmittance of the bulk tellurite was measured using a Fourier transform infrared spectrometer on a 3 mm long sample. Due to the stoichiometry of the glass, the transmittance is quite flat and high far out into the near infrared, in contrast to previously reported work [13]. This transmittance of 75% translates to a minimum loss figure of 1.8 dBm^{-1} at 1420 nm that increases to 8 dBm^{-1} at 1750 nm in the fiber measured using the cutback technique. This transmittance makes the tellurite glass useful for SC generation into the infrared. As previously mentioned, the increased loss at longer wavelengths is mitigated by the very short length (8 mm) of the PCF used. Figure 2 also shows the measured group velocity dispersion of the bulk tellurite and of the tellurite PCF, obtained by using low coherence (white light) interferometry [14]. The dispersion curve in Fig. 2 does not span the entire bandwidth of the supercontinuum due to limitations of the instrumentation used in the measurement. If we assume the dispersion curve follows a parabolic path there is, potentially, another zero dispersion wavelength at approximately 4.5 μm. The fiber appears to be single mode at the pump wavelength of 1550 nm showing a quasi-Gaussian fundamental mode profile. As intended, the design of the waveguide shifts the zero dispersion wavelength of the fiber to 1380 nm, below the SC pump wavelength of 1550 nm so that the pump pulse propagates in the region of anomalous dispersion. The effective area of the fiber mode is 1.7 μm^2. Combined with a non-linear index $n_2 = 2.5 \text{ X } 10^{-19} \text{ m}^2\text{W}^{-1}$, the nonlinear waveguide coefficient is calculated to be $\gamma = 596 \text{ km}^{-1}\text{W}^{-1}$. This nonlinearity is greater than other tellurite fiber designs ($\gamma = 48 \text{ km}^{-1}\text{W}^{-1}$) [13] and significantly larger than the one found for commercial high-Δ silica PCFs ($\gamma = 34$ to $215 \text{ km}^{-1}\text{W}^{-1}$) [15].

3. Experimental setup

SC generation is achieved by coupling ultra-short pulses into an 8 mm length of tellurite PCF. Pulses are generated by an optical parametric oscillator (OPO) pumped by a Ti:Sapphire laser centered at 810 nm. The OPO generates pulses with a central wavelength of 1550 nm, with a pulse width of 110 fs, average power of 250 mW at a repetition rate of 80 MHz. The pump beam power is controlled using a half wave plate and a polarizing beam splitter. The orientation of the pump beams major polarization axis with respect to the fiber microstructure is controlled by a second wave plate.

Figure 3 outlines the experimental setup. After the pulses are generated they are focused using a 40X 0.5 NA aspheric lens into the tellurite fiber. The average power at the input face of the fiber is measured to be 150 mW. The fiber is cleaved by hand using a diamond stylus into sub centimeter segments. These pieces are mounted onto customized modular fiber holders. At the output face of the PCF, the resulting SC, is delivered to several instruments for characterization after being collimated using another 40X, 0.65 NA objective lens. The SC output power is measured to be 70 mW resulting in slightly under 50% coupling efficiency. The first instrument is an optical spectrum analyzer (OSA) whose wavelength range is 350 to 1750 nm with a resolution of 1 nm. The OSA is designed for fiber coupling; however, the output from the tellurite fiber is focused onto the input using the optics described above. The second instrument is a grating monochromator whose gratings are designed to diffract wavelengths between 1500 to 8000 nm (300 lines per mm, 3000 nm blaze and 150 lines per mm, 4000nm blaze) in combination. The detectors used are an un-cooled lead-selenide detector whose range extends from 1500 to 4500 nm and a liquid nitrogen cooled mercury-cadmium-telluride detector with a range of 2000 to 12000 nm. The imaging slits of the monochromator are set to give a wavelength resolution of 5 nm. The signal analyzed by the

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monochromator is detected with a lock-in amplifier connected to an optical chopper that modulates the beam entering the monochromator at a frequency of 312 Hz. Both the OSA and the monochromator are placed so that the optical path lengths between the PCF end and the instruments are the same, to account for the chromatic aberration in the collimating objective lens. Given the large bandwidth of this SC, special care needs to be taken using a monochromator to measure the spectrum, lest higher wavelengths are adulterated by higher-order diffraction of shorter wavelengths. This is achieved using a pair of semiconductor, long-wavelength pass filters, one with a cut-off of 2 µm and the other at 4.16 µm. Combined with the response of the grating used (1500 nm to 8000 nm) these filters effectively allow only the fundamental diffracted order to pass through the monochromator from a wavelength range between 1500 and 5500 nm.

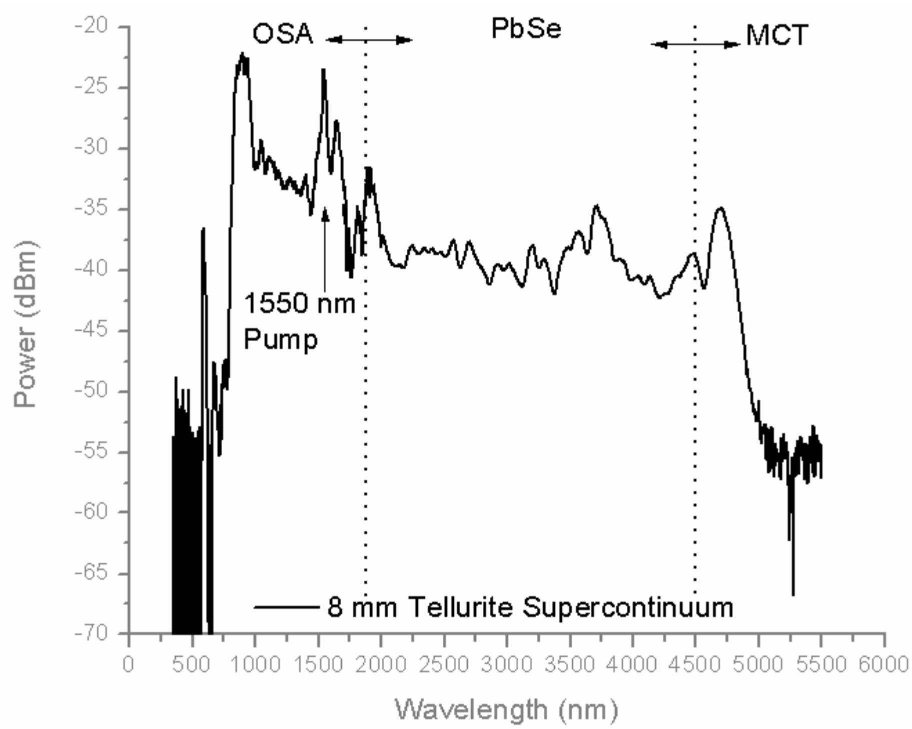

Fig. 3. Spectral response of the SC generated by the 8 mm segment of Tellurite PCF. The wavelength regions analyzed by the OSA and the monochromator with lead selenide (PbSe) or mercury cadmium telluride (MCT) detectors are indicated. Also indicated is the pump wavelength of 1550 nm.

4. Results and discussion

Figure 4 shows the SC spectrum from the 8 mm length of tellurite fiber. The spectrum extends from a wavelength of 789 nm to 4080 nm measured at -45 dBm. Figure 4 also shows the position of the 1550 nm pump wavelength and the wavelength regions where different detectors were used. Aside from the obvious spectral bandwidth, there are several other features of the spectrum that warrant mention; there is a sharp edge at the short wavelength side of the SC spectrum at 789 nm and general structure over the SC bandwidth pedestal. The spectral structure at the short wavelength end of the pedestal compared to the long wavelength side is simply the result of the optical spectrum analyzers higher wavelength resolution being presented on a compressed axis making the spectrum appear noisier at lower wavelengths.

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The nature of the spectral pedestal is different to that in previous work with different PCF glass formulations (flint silica glass SF6) at similar sub-cm lengths, where a more symmetric, smoother, broad bandwidth SC is observed when pumped under the same pulse conditions [10, 11]. Using the parameters given above for the tellurite PCF and pump pulses (β_2 = 80 ps^2km^{-1}, P_0 = 7954 W, γ = 596 $km^{-1}W^{-1}$, T_{FWHM} = 110 fs) the nonlinear length of the tellurite PCF is calculated at L_{NL} = 0.21 mm, the dispersion length L_D = 38 mm [5]. From these characteristic length scales, the soliton number found in the tellurite fiber is N = 14 indicating that higher order soliton dynamics affect the spectral characteristics of the supercontinuum radiation generated in this fiber. [16]. The soliton fission length inside this fiber is 3 mm [5], less than the total length of the tellurite fiber and soliton period of 60 mm. This reinforces the fact that, with PCFs of high bulk nonlinearity, high-order effects occur in the very first instances of propagation. Figure 4 also shows the sharp spectral edge at the blue side of the spectrum at 789 nm. This sharp cutoff combined with the strong peak just before it is suggestive of dispersive wave formation [5,17,18] (Cherenkov radiation [18]). The wavelength of the dispersive wave radiation is calculated using the phase matching relationship in [16] and the fiber dispersion parameter measured above and is found to 860 nm. While this figure gives an approximate location of the dispersive wave radiation, there is clearly some discrepancy. This is potentially due to inaccuracies in measuring the PCF dispersion curve and the implicit approximation in the phase matching expression for the dispersive wave radiation that the propagating soliton wavenumber remains constant as the wave propagates, which is not necessarily true for the higher order solitons that could be propagating in this PCF [17]. Indeed, reference [17] predicts a blue shift of the dispersive wave radiation which is also seen experimentally in these results. From these considerations, we conclude that in these sub-cm lengths of highly nonlinear fiber higher order soliton fission is responsible for SC generation. The precise nature of SC generation in this regime requires numerical investigation that is the subject of further work. We also observe the generation of light at a wavelength of 585 nm. The origin of this spectral peak is unclear and is also the subject of further investigation.

Prior work [8,19,20] has been performed in generating SC across the near- to mid-IR wavelength region. In [19, 20] SC light spanning between 800 nm to 3.5 μm was demonstrated in various lengths (between 10 m and 80 m) of two formulations of ZBLAN (zirconium, barium, lanthanum, aluminium, sodium) fluoride fiber joined with 3 m of silica single mode fiber. This scheme, while covering similar SC bandwidths using pump pulses at 1550 nm at comparable peak powers, is disparate to the SC generation presented here when comparing the lengths of the nonlinear fiber used. For applications where cost is an issue, a short length of nonlinear PCF is preferable. In a recent review [8], a number of glass formulations are presented for addressing SC generation into the mid-IR, including other tellurite formulations. While these other glasses (such as selenides and sulfur glasses) have very high refractive indices and modal confinements (and thus higher waveguide nonlinearities) their losses are typically much greater than tellurite used in the PCF here. Generally, the waveguides in [8] are not pumped at telecommunications wavelengths and those that are do not possess the SC bandwidth generated by the tellurite PCF demonstrated here. The bismuth glass formulations in [8] provide similar SC bandwidths to those demonstrated here in relatively short lengths (40 mm), however, they are pumped at 2.0 μm which is, again, not accessible to telecommunications hardware. Other tellurite formulations are also presented in [8] but the waveguides described there have a ZDW at 2240 nm which also is outside the telecommunications wavelength range. A recent demonstration [21] uses 7 mm, 300 mm and 2100 mm of tellurite microstructured optical fiber with a similar design to that presented here with a slightly higher γ = 675 $W^{-1}km^{-1}$ pumped with pulse energies up to 230 pJ. This pump energy is around 5 times lower than that used here (1 nJ) and the bandwidth generated is also lower, from 950 to 2100 nm.

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7. Conclusion

In conclusion, we have demonstrated the generation of 90 mW average power SC in a sub-centimeter segment of highly nonlinear tellurite glass photonic crystal fiber. The SC output has a very broad wavelength range, spanning at least two and a half optical octaves, comparable to the bandwidth available in bismuth fibers to date, using significantly shorter lengths of fiber pumped using telecommunications wavelengths that will enable expedient and economical assembly of tellurite-based SC sources. These characteristics make SC light generated by short nonlinear PCFs and tellurite PCFs specifically, promising for applications requiring fiber based near- to mid-IR.

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* Permanent address: CePOF, Instituto de Fisica Gleb Wataghin, Cidade Universitaria Zeferino Vaz, Barao Geraldo 13083-970, Campinas SP, Brazil

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