Evaluation of chirped-pulse-amplification systems with Offner triplet telescope stretchers

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We present an analytical phase expression for an Offner triplet telescope stretcher based on ray tracing and apply it to analyze a chirped-pulse-amplification (CPA) system that includes an Offner stretcher. The results of our calculations show that the aberration caused by an off-center grating arrangement of an Offner stretcher can be used to cancel out the material dispersion of the CPA system. The optimization of the grating position provides a flat and broadband phase window for the CPA system, which leads to high-fidelity recompressed pulses. © 2002 Optical Society of America

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1. INTRODUCTION

Since the invention of the chirped pulse amplification (CPA) technique for generating ultraintense femtosecond pulses,[1,2] the peak power of femtosecond laser pulses has been boosted to multiterawatt and even petawatt levels.[3–5] In a CPA system, a seed pulse is stretched by a stretcher to a picosecond or a nanosecond time range, then seeded to an amplifier, and finally recompressed to its original width. The stretcher can be an optical fiber, a piece of bulk dispersive material, or a grating-telescope stretcher,[5–10] all of which provide positive dispersion. A compressor that makes use of either a prism pair or a grating pair offers negative dispersion to cancel out the positive dispersion that occurs in the stretching and the amplifying processes.

To extract high-fidelity amplified pulses from a CPA system it is important to control the phase of the entire system, which includes a stretcher, an amplifier, and a compressor. With the formulas given by Treacy[11] and Martinez,[10] calculation of the phase of a standard stretcher is possible only for the central wavelength. One can calculate the first few orders of the phase, including the group delay, the group-delay dispersion, the third-order dispersion, and the fourth-order dispersion of a CPA system in the central wavelength. Recent research, however, has shown that a CPA system based on evaluation of the group delay, the group-delay dispersion, and the third- and fourth-order dispersion in the central wavelength only is not able to produce high-fidelity amplified pulses because the phase is not always monotonic as a function of wavelength. It is therefore necessary to introduce an exact expression for the total phase of a CPA system, which makes it possible to calculate all-order dispersions over the entire wavelength range of the spectrum of a pulse and to optimize the system such that it can provide a flat and broadband phase window.

Formulating an exact expression is difficult because a precise calculation of a stretcher cannot be made, inasmuch as there is no analytical expression available for a stretcher. Therefore, in many cases, the phase of the stretcher has been considered to be the same as that of the compressor, except for having an opposite sign. A more scientific evaluation system uses ray tracing. One may make use of a commercially available software package or develop one's own to calculate the optical path for as many wavelengths as one can and then do a curve fitting over the entire wavelength range of the spectrum of a pulse to carry out the analytical evaluation of a stretcher. It should be noted, however, that the use of insufficient data points for polynomial curve fitting can sometimes result in large errors when one is using derivatives.

The purpose of this study is to derive a simple and useful expression with which to calculate the phase of an Offner stretcher.[8,12] The expression derived indicates that the Offner stretcher is not always aberration free. This aberration leads to high-order dispersion and affects the performance of a CPA system. It was found that the optimization of the Offner stretcher arrangement provides a flat and broadband phase window for a CPA system to ensure high-fidelity recompressed pulses.

2. PHASE OF THE OFFNER STRETCHER

A. Single-Mirror Aberration-Free Stretcher

A single-mirror aberration-free stretcher model was proposed by Zhang *et al.*[13] for a demonstration of how a stretcher is a conjugation of a compressor. The complete phase expression is

$$\Phi_s = (\omega/c)[4R - b(1 + \cos\theta)] + 2\pi G d^{-1}\tan(\gamma - \theta), \tag{1}$$

where λ is the wavelength and d is the groove space of the gratings. Incident angle γ and diffraction angle $\gamma - \theta$ satisfy the grating equation. The second term in Eq. (1), $2\pi G d^{-1}\tan(\gamma - \theta)$, is the so-called phase-correction term introduced by Treacy.[11]

By comparing Eq. (1) with the phase expression of a compressor derived by Treacy,[11] one can easily understand that the grating single-mirror stretcher is an exact conjugation of the compressor. Note that no approximation is made for deriving Eq. (1); therefore this grating single-mirror stretcher configuration is free from spherical aberration and considered an ideal aberration-free stretcher. However, this grating single-mirror stretcher has only theoretical significance because in practice a laser beam must have a finite size and will diverge as it passes through the grating single-mirror system. Therefore re-collecting the laser beam will require use of a telescope system in place of a single mirror.

B. Aberration-Free Offner Stretcher

There is an alternative design that exhibits no aberration and makes use of an Offner triplet telescope. In this design, two gratings are arranged in parallel and separated by a perpendicular distance G. One convex mirror with radius of curvature $-R/2$ is located concentrically with a concave mirror, and the incident spot on grating 1 is aligned with the spherical centers of the two mirrors. This configuration, which is shown in Fig. 1, is often referred to as an Offner stretcher.

Following a ray-tracing method that is similar to the one used in the research reported in Ref. 13, we can easily derive a phase expression for this kind of Offner stretcher:

$$\Phi_s = \frac{\omega}{c}[5R - b(1 + \cos\theta)] + 2\pi G d^{-1}\tan(\gamma - \theta). \tag{2}$$

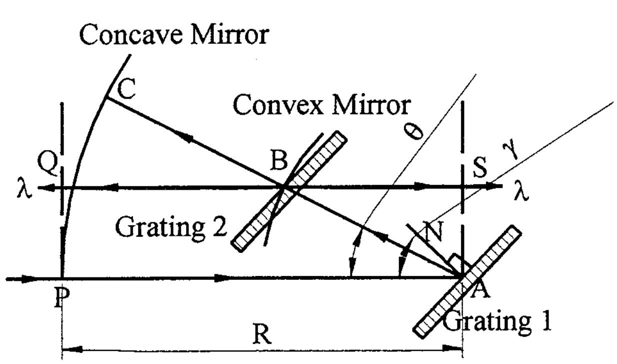

Fig. 1. Schematic of an Offner triplet stretcher with a pair of gratings. Labels are defined in text.

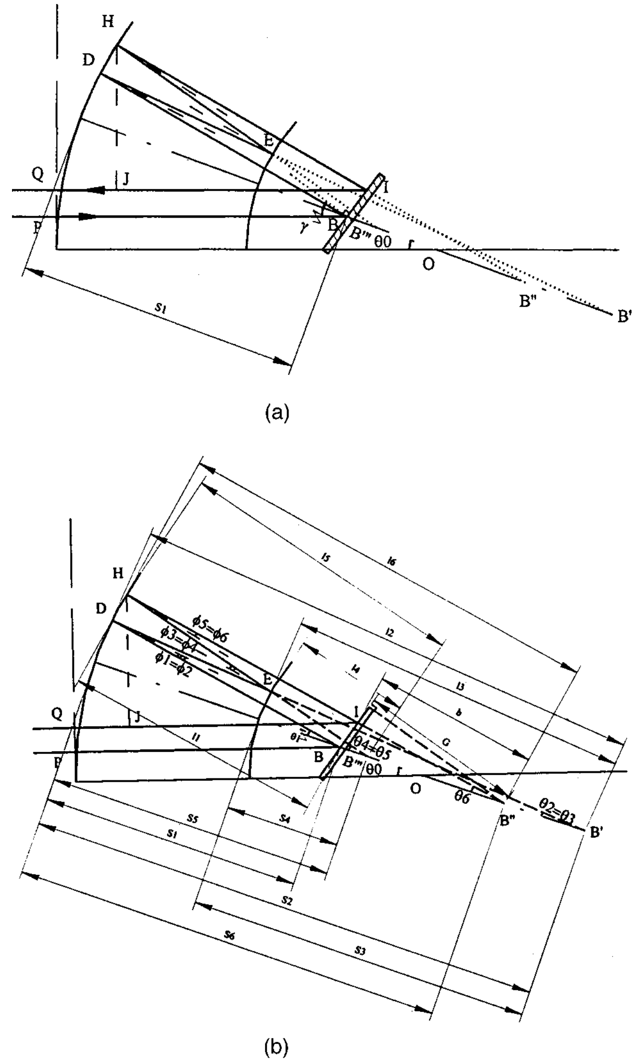

Fig. 2. Schematics of a single-grating Offner triplet stretcher including (a) only the design parameters and (b) all the angles and distances.

The only difference between Eq. (2) and the phase expression of the single-mirror aberration-free stretcher is in a constant. Thus this type of Offner stretcher is aberration free.

C. Off-Center Offner Stretcher

An off-center grating arrangement with a single grating is often preferred for its convenience in practical use. As shown in Fig. 2, the axis of the system has a constant angle θ_0 with respect to the horizontal reference line, where θ_0 is the difference between the incident and the diffractive angles at central wavelength λ_0. For an arbitrary ray diffracted by the grating at an angle θ_1 to the system axis, the diffractive angle becomes

$$\gamma - \theta = \gamma - (\theta_0 + \theta_1). \tag{3}$$

The optical beam that passes through point P is incident at an angle γ at B on the grating. The diffracted beam bounces between two spherical mirrors, following paths PB, BD, DE, EH, and HI, and returns to the grating at an angle θ_6; the collimated beam leaves the system at Q. The total path length is expressed as

$$p = P_0 + P_1 + P_2 + P_3 + P_4 + P_5 + P_6, \tag{4}$$

where P_i are defined as

$$P_0 = PB = l_0, \tag{5a}$$

$$P_1 = BD = l_1, \tag{5b}$$

$$P_2 = DE = l_2 - l_3, \tag{5c}$$

$$P_3 = EH = l_5 - l_4, \tag{5d}$$

$$P_4 = HI = l_6 - b, \tag{5e}$$

$$\begin{aligned} P_5 &= IQ = IJ + JQ \\ &= (l_6 - b)\cos(\theta_0 + \theta_6) \\ &\quad + [R - l_6\cos(\theta_0 + \theta_6) + (s_6 - R)\cos\theta_0]. \end{aligned} \tag{5f}$$

The ray-tracing parameters used in Eqs. (5) are defined in Appendix A. $b = AI$ is assumed to be the distance of the slant between the diffraction grating and its image. Perpendicular distance G between the grating and the image grating is expressed as

$$G = (s_6 - s_1)\cos(\gamma - \theta_0). \tag{6}$$

Then we obtain the slant distance b, expressed as

$$b = \frac{G}{\cos(\gamma - \theta_0 - \theta_6)} = (s_6 - s_1)\frac{\cos(\gamma - \theta_0)}{\cos(\gamma - \theta_0 - \theta_6)}. \tag{7}$$

Here we classify the expression for the total optical path p by using three terms, as follows:

$$p = C + A - D, \tag{8}$$

where

$$C = 2R - (R - s_1)\cos\theta_0, \tag{9}$$

$$\begin{aligned} A = R\Bigg[&\sin(\theta_1 - \phi_1)\left(\frac{1}{\sin\theta_1} + \frac{1}{\sin\theta_2}\right) \\ &- \frac{1}{2}\sin(\theta_3 + \phi_3)\left(\frac{1}{\sin\theta_3} + \frac{1}{\sin\theta_4}\right) \\ &+ \sin(\theta_5 - \phi_5)\left(\frac{1}{\sin\theta_5} + \frac{1}{\sin\theta_6}\right)\Bigg] \\ &+ R\frac{\sin\phi_6}{\sin\theta_6}\cos\theta_0, \end{aligned} \tag{10}$$

$$\begin{aligned} D &= \frac{G}{\cos(\gamma - \theta_0 - \theta_6)}[1 + \cos(\theta_0 + \theta_6)] \\ &= b[1 + \cos(\theta_0 + \theta_6)]. \end{aligned} \tag{11}$$

The first term, denoted C, is a constant; A is the mirror's spherical aberration factor, and D is the optical path that dominates the group delay of the Offner stretcher. It should be noted that Eq. (11) is similar to the expression for Treacy's grating-pair compressor, and its existence shows again the conjugation relation between the stretcher and the compressor.

The phase-correction term in such a stretcher should be similar to that of a grating single-mirror stretcher, that is,

$$2\pi G d^{-1}\tan(\gamma - \theta_0 - \theta_6). \tag{12}$$

Because s_6 is not a constant, G is not a constant either. This causes a reference point shift. To correct this reference point shift we introduce an additional phase term,

$$2\pi(G_0 - G)d^{-1}\tan(\gamma - \theta_0), \tag{13}$$

where G_0 represents the perpendicular distance between the gratings when θ_6 equals zero and is expressed as

$$G_0 = (2R - 2s_1)\cos(\gamma - \theta_0). \tag{14}$$

Consequently, the maximum slant distance is given as

$$b_0 = 2R - 2s_1. \tag{15}$$

From the above discussion, the total phase of the off-center Offner stretcher should be

$$\begin{aligned} \Phi_s = &\frac{\omega}{c}(C + A) - \frac{\omega}{c}b[1 + \cos(\theta_0 + \theta_6)] \\ &+ \frac{2\pi G}{d}[\tan(\gamma - \theta_0 - \theta_6) - \tan(\gamma - \theta_0)] \\ &+ \frac{2\pi G_0}{d}\tan(\gamma - \theta_0). \end{aligned} \tag{16}$$

Now we have obtained an analytical expression with which to calculate the phase of the off-center Offner stretcher, which has a form that is similar to that of a compressor, except that it has a negative sign and that some more terms related to the mirror aberration are different. Note that the slant distance is approximately twice that of a Martinez stretcher, for which $b_0 = R - 2s_1$.[13] Using this expression, we could extract the group delay and the subsequent higher orders of the phase over the entire wavelength range of the spectrum of a pulse. Of course, many parameters in Eq. (16), such as A, C, b, G, and θ_1, have to be calculated through ray-tracing formulas, as we have done in Appendix A. That makes the calculation complicated. However, we believe that careful writing of the program code would make the calculation easy and straightforward. The only independent parameters needed to be input are R, s_1, d, γ, and λ_0.

Notice that the above equations are only two-dimensional. A vertical tilt out of the diffraction plane has to be allowed for passage of a real beam. If the tilt is small enough, the dominant aberration of this telescope will still be spherical. We conducted the three-dimensional calculation and found that, if the vertical tilt is less than 4°, the delay error caused by the tilt is within 2 fs in the wavelength range from 750 to 900 nm.

3. EVALUATION OF THE DISPERSION OF AN OFFNER STRETCHER

Equations (1) and (16) indicate that an Offner stretcher is aberration free only if the incident grating is placed at the

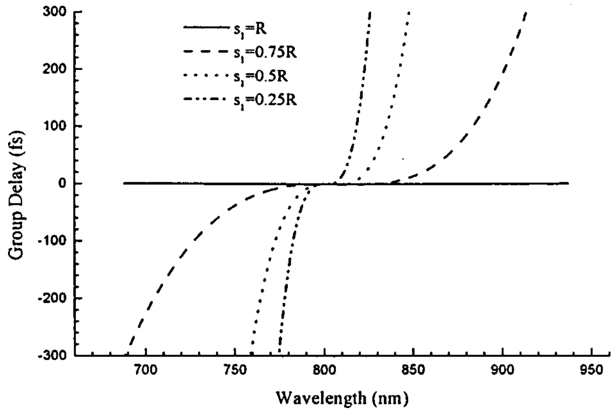

Fig. 3. Calculated residual group delay of a single-grating Offner stretcher and a conjugate compressor system for some positions of the grating in the Offner stretcher. Material dispersion is not considered.

center of curvature of the spherical mirrors. However, the single-grating Offner stretcher requires that the grating be placed off the center of the spherical mirrors, which causes mirror spherical aberration. As the grating gets closer to the mirrors, the amount of the aberration becomes larger. To evaluate an Offner stretcher we calculated the residual group delay for various grating positions for the stretcher compensated by a conjugate compressor. The radii of curvature of the two mirrors are 1000 and −500 mm, and the groove density of the grating is 1200 lines/mm. The angle of incidence upon the grating is 38.68°, and central wavelength λ_0 is 800 nm. The material dispersion of the amplifier is not included in this calculation. Figure 3 shows the results calculated over a broadband wavelength range.

We can easily find (see Fig. 3) that the Offner stretcher is aberration free only if the grating is placed near the center of the curvature ($s_1 \cong R$). As the grating is moved away from the center to the concave mirror ($s_1 = 0.75R$), the aberration-free bandwidth becomes narrower. When the grating is moved further away from the center and placed on the halfway between the center and the concave mirror ($s_1 = 0.5R$), the aberration-free bandwidth becomes much narrower. When the grating of the Offner stretcher is placed at $s_1 = 0.25R$, the absolute values of the residual group delay increase rapidly with wavelength, which results in an extremely narrow aberration-free bandwidth. Figure 3 shows that the Offner stretcher is not always aberration free and that in most cases the aberration is too large to be neglected.

4. OPTIMIZATION OF A CHIRPED-PULSE AMPLIFICATION SYSTEM

The aberration characteristic of an Offner stretcher is not a negative factor because we can use it to cancel out the material dispersion in a CPA system. For the generation of high-fidelity recompressed pulses in a CPA system it is more important to control the phase of the system than to care about the aberration of the stretcher. One may use the aberration converted into dispersion to cancel out the material dispersion and provide a flat broadband phase window for the whole CPA system. To prove this, we calculated the residual group delay of a CPA system over the entire wavelength range of a pulse spectrum and the pulse shape of a recompressed pulse that is leaving the CPA system.

We chose a typical multipass amplification system as an example. A pulse from an oscillator underwent one pass to a pulse picker (which consists of a 20-mm-long KD*P Pockels cell and two 19-mm-long calcite polarizers), three passes to an isolator (which consists of a 40-mm terbium gallium garnet crystal and two 19-mm-long calcite polarizers) and eight passes to a 10-mm long Ti:sapphire crystal. The Offner stretcher was the same as that described in Section 3. The incident angle on the grating was still 38.68°. We calculated the residual group delay of the total amplification system for three grating positions and obtained three typical residual group delay curves, as shown in Fig. 4. For grating positions $s_1 = 0.55R$ and $s_1 = 0.7R$ the residual group delay shows a narrow flat region. The curve for $s_1 = 0.55R$ indicates that the material dispersion was not enough to cancel out the mirror aberration, whereas the curve for $s_1 = 0.7R$ means that the material dispersion was too large to be canceled by the mirror aberration. These calculation results allowed us to expect the existence of an optimum grating position where the material dispersion is almost completely canceled out by the mirror aberration. This position was found to be $s_1 = 0.63R$ (which corresponds to a slant distance of $0.74R$), where the group delay represents a broad flatness of ~100 nm near 800 nm.

Suppose that a 20-fs chirp-free pulse is incident into the CPA system described above. This incident pulse is stretched to 434 ps after it passes through the stretcher four times. The stretching ratio is 21700. Figure 5(a) shows how the duration of the output pulse from the CPA system depends on the grating position of the Offner stretcher. For grating positions either too far from or too close to the center of curvature of the spherical mirrors the recompressed pulses have wings and broader pulse widths than the initial pulse width. Only grating position $s_1 = 0.63R$ makes a nearly perfect recompressed pulse of 22 fs possible. Figure 5(b) shows the contrast of the intensity of the output pulse from the CPA system.

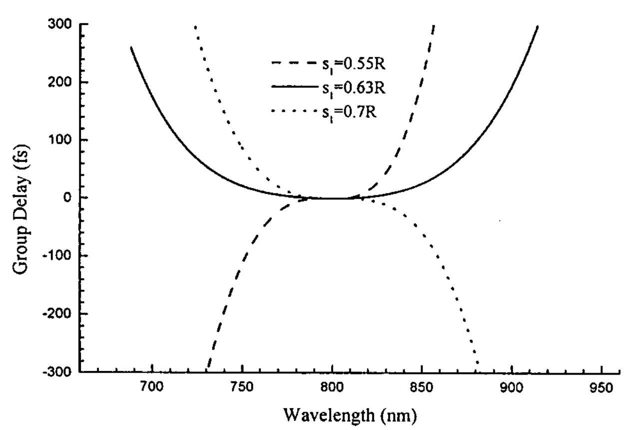

Fig. 4. Calculated residual group delay of a typical CPA system, which consists of a single-grating Offner stretcher, an amplifier, and a compressor. The results are shown for various positions of the grating in the Offner stretcher.

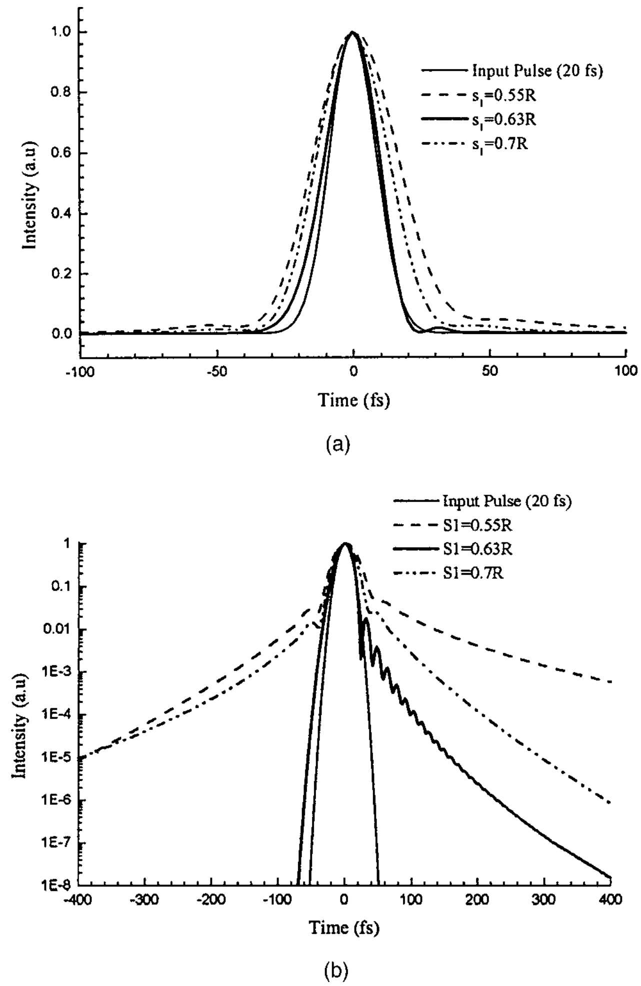

Fig. 5. Simulation of the pulse intensity shapes of recompressed pulses that are leaving a CPA system for various positions of the grating in an Offner stretcher (a) on a linear scale and (b) on a logarithmic scale. A 20-fs chirp-free incident pulse is assumed. The stretched pulse at a grating position $s_1 = 0.63R$ is recompressed to 22 fs by a conjugate compressor.

These results show that one can use Eq. (16) derived from ray tracing to determine the optimal grating position of the Offner stretcher, which can lead to the shortest recompressed pulse from a CPA system.

5. CONCLUSIONS

We have derived a set of simple and useful expressions based on ray tracing with which to calculate the phase of an Offner stretcher. The phase expression for the Offner stretcher has shown that the stretcher is aberration free only if the grating is placed at the center of curvature of the spherical mirrors. A phase evaluation of a typical CPA system has revealed that the aberration caused by the off-center grating arrangement of an Offner stretcher can be used to cancel out the material dispersion of the CPA system. By optimizing the position of the grating in the Offner stretcher, we can obtain from the CPA system a flat and broadband phase window for generating high-fidelity laser pulses. The computer simulation has also indicated that the optimized system is able to recompress a 20-fs pulse almost completely under the conditions that there are no nonlinear effects such as gain narrowing and self-phase modulation in the CPA system.

APPENDIX A. RAY TRACING

Ray tracing gives us the complete ray path length of the Offner stretcher (refer to Fig. 2). The total optical path length in Fig. 2 is summarized as

$$\begin{aligned} p = {} & l_0 + l_1 + l_2 - l_3 + l_5 - l_4 + (l_6 - b) \\ & \times [1 + \cos(\theta_0 + \theta_6)] + R \\ & - [l_6 \cos(\theta_0 + \theta_6) - (s_6 - R)\cos\theta_0], \end{aligned} \tag{A1}$$

where l_0, l_1, l_2, l_3, l_4, l_5, and l_6 are related to the following ray trace:

$$l_0 = R\left[1 - \left(1 - \frac{s_1}{R}\right)\cos\theta_0\right], \tag{A2}$$

$$\sin\phi_1 = \left(1 - \frac{s_1}{R}\right)\sin\theta_1, \tag{A3}$$

$$\phi_2 = \phi_1, \tag{A4}$$

$$\theta_2 = \theta_1 - 2\phi_1, \tag{A5}$$

$$s_2 = R\left(1 + \frac{\sin\phi_2}{\sin\theta_2}\right), \tag{A6}$$

$$l_1 = R\,\frac{\sin(\theta_1 - \phi_1)}{\sin\theta_1}, \tag{A7}$$

$$l_2 = R\,\frac{\sin(\theta_1 - \phi_1)}{\sin\theta_2}, \tag{A8}$$

$$s_3 = s_2 - R/2, \tag{A9}$$

$$\theta_3 = \theta_2, \tag{A10}$$

$$\sin\phi_3 = \left(\frac{s_3}{R/2} - 1\right)\sin\theta_3, \tag{A11}$$

$$\phi_4 = \phi_3, \tag{A12}$$

$$\theta_4 = \theta_3 + 2\phi_3, \tag{A13}$$

$$s_4 = \frac{R}{2}\left(1 - \frac{\sin\phi_3}{\sin\theta_4}\right), \tag{A14}$$

$$l_3 = \frac{R}{2}\,\frac{\sin(\theta_3 + \phi_3)}{\sin\theta_3}, \tag{A15}$$

$$l_4 = \frac{R}{2}\,\frac{\sin(\theta_3 + \phi_3)}{\sin\theta_4}, \tag{A16}$$

$$s_5 = s_4 + R/2, \tag{A17}$$

$$\theta_5 = \theta_4, \tag{A18}$$

$$\sin\phi_5 = \left(1 - \frac{s_5}{R}\right)\sin\theta_5, \tag{A19}$$

$$\phi_6 = \phi_5, \tag{A20}$$

$$\theta_6 = \theta_5 - 2\phi_5, \tag{A21}$$

$$s_6 = R\left(1 + \frac{\sin \phi_6}{\sin \theta_6}\right), \tag{A22}$$

$$l_5 = R\,\frac{\sin(\theta_5 - \phi_5)}{\sin \theta_5}, \tag{A23}$$

$$l_6 = R\,\frac{\sin(\theta_5 - \phi_5)}{\sin \theta_6}. \tag{A24}$$

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