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Control of temperature fields and melt formation in laser transmission welding using adapted wavelengths

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Abstract

The usage of laser transmission welding of polymers as a joining technique in industrial applications is often limited by the optical properties of the joining partners and the limited gap-bridging capability. By using alternative laser wavelengths or multiple beam sources it is possible to adjust the radiation to the properties of the materials and increase the weld seam quality. Especially for scattering materials, parts without specific laser absorbing additives and in applications where relatively large gaps occur due to manufacturing tolerances of the parts, adapted wavelengths can lead to improved results. In this work, the gap bridging during quasi-simultaneous laser transmission welding is investigated in welding experiments and thermomechanical FE-simulations. Usage of a laser wavelength in the range of 2.0 µm is found to be beneficial in terms of gap-bridging, compared to usually applied diode or solid state lasers emitting at about 1 µm due to the higher intrinsic absorption in unmodified thermoplastic materials. This leads to increased temperatures in the transparent joining partner and therefore greater thermal expansion. Furthermore the radiation shows an increased penetration depth in carbon black filled, laser absorbing materials, also leading to increased thermal expansion and improved gap bridging. The wavelength of 2.0 µm is also found to improve the strength of weld seams when turbid materials or materials with scattering additives are used as laser transparent parts, since scattering at small particles is strongly wavelength dependent, so the longer wavelength features better control of the resulting intensity distribution in the joining zone.

Keywords: laser transmission welding; adapted wavelength; melt pool geometry; gap bridging;

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1. Introduction

Laser transmission welding (LTW) is a flexible, quick and reliable method for the joining of polymers and is widely used in industrial applications. In most cases, near-infrared diode or solid state beam sources, emitting at around 1 µm are used, since these lasers are relatively inexpensive and most polymeric materials show high transmission of these wavelengths, Klein, 2011 and Russek, 2006. This allows the laser beam to be transmitted almost unaffectedly through a transparent part to the joining interface were the radiation is absorbed by the second joining partner. Usually an opaque material, for example a carbon-black filled polymer, or an absorbing intermediate layer is used to absorb the radiation, leading to a temperature rise and the creation of a weld seam between the two parts.

However, there are several factors limiting the applicability of LTW with these beam sources. Due to the concentrated heat generation at the surface of the absorbing part, there is a high risk of thermal damaging of the material if heat conduction to the transparent joining partner is prevented by an air gap between the parts, v. d. Ven and Erdman, 2007. The capability to close residual gaps during welding is essential for reliable welding results and a robust process, Chen, 2009. Furthermore, scattering at crystallite structures and particulate or fibrous additives inside the material can affect the formation of a weld seam, when the intensity of the transmitted radiation is insufficient for the melting of the material, Devrient et. al, 2012.

Since the optical material properties of polymers, especially the absorbance and scattering behavior are strongly wavelength-dependent, the choice of laser wavelengths adapted to the material properties and the part geometry can help to overcome some of these limitations and improve the weld quality. Most research of laser transmission welding of polymers with alternative laser wavelengths concentrates on welding of similar materials without laser absorbing additives by using the intrinsic absorption properties of the materials, Mingareev et. al, 2012, Mamuschkin et. al, 2014 and Ruotsalainen et. al, 2015. It has also been demonstrated, that the application of alternative laser wavelengths can enable successful welding of strongly scattering materials, Mamuschkin et. al, 2013.

In this work, the influence of adapted laser wavelengths on the quasi-simultaneous LTW-process between unmodified materials and materials with added absorber in overlap joints is investigated in welding experiments and thermomechanical Finite Element (FE)-Simulations. Especially the possibilities to modify the temperature fields and the weld seam geometries and the influence on the gap-bridging behavior are considered. Additionally the wavelength-dependent scattering behavior of several thermoplastic materials is investigated over a spectral range of 810 nm to 2000 nm to support the choice of a suitable beam source among the most relevant commercially available laser systems for LTW. To demonstrate the potential of this approach tensile shear strengths of welds between scattering materials are compared for two different laser wavelengths.

2. Experimental

2.1. Investigation of spectral scattering-behavior

To investigate the wavelength-dependent scattering behavior of thermoplastic materials an experimental setup as schematically shown in Fig. 1 was used. Two equally sized apertures with a diameter of 5 mm were placed in front of the entrance of an integrating sphere of a spectrometer (Lambda 1050, Perkin Elmer, USA). Material samples with a thickness of 2 mm were placed in the beam path of the spectrometer between the two apertures. By comparing the ratio between the remaining light intensity to the initial radiation transmitted through the sample with only the first aperture in place, the portion of the radiation which was scattered out of the initial parallel beam path was determined.

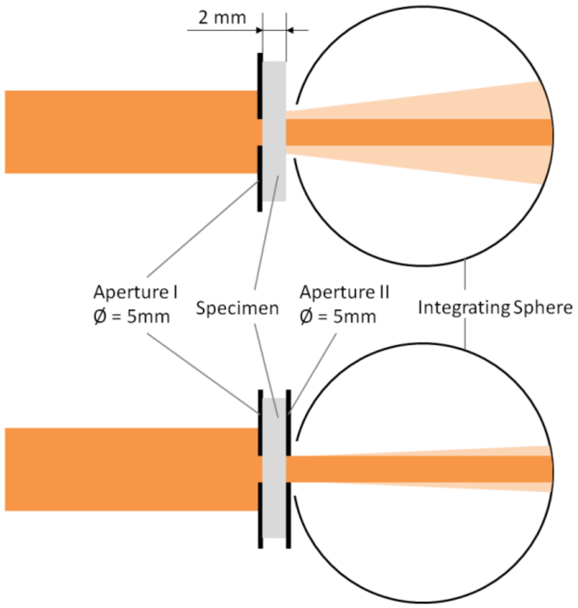


Fig. 1. Setup for investigating the spectral scattering properties of polymers using a spectrometer with integrating sphere (not to scale);

The aperture size of 5 mm was selected to reduce the influence of diffraction by using a relatively large diameter compared to the sample thickness while ensuring that all the scattered radiation could be captured by the entrance hole of the integrating sphere.

The determined scattering properties, along with the absorption and thermal properties were used as input parameters for thermomechanical Finite Element (FE) simulations to investigate the melt pool geometry and the gap-bridging process, as described in Schkutow and Frick, 2016.

2.2. Welding experiments

Welding experiments were carried out using two different beam sources, a fiber coupled diode laser system (Dilas Mini, Dilas Diodenlaser, Germany), emitting at 980 nm with a maximum power of 50 W and a Thulium-fiber laser (RevoLix jr., LISA laser products, Germany) emitting at 2000 nm with a maximum power of 30 W. The utilized process variant was quasi-simultaneous welding, with the entire weld seam being irradiated multiple times at a frequency of 5 Hz, using a flying optics approach, with the focusing system being linearly moved along the weld contour with a feed rate of 450 mm/s using a linear stage (DXL-LM155, ETEL S.A., Switzerland). The focusing system consisted of a tilted mirror and a plano-convex focusing lens, realizing a beam diameter of 1.8 mm in the joining plane. Specimens were arranged in an overlap configuration and fixed by a clamping device, using a clamping pressure of approximately 1 MPa.

To investigate the gap bridging process glass spacers were placed between the two joining partners before clamping to create an air gap with a width of 6 mm and heights of 130 µm. For the welding of these samples the same quasi-simultaneous approach as described above was used.

The influence of scattering materials as the transparent joining partner was investigated in overlap welding experiments between turbid unfilled ABS as the transparent part and ABS filled with 0.25 wt.-% carbon black as the absorbing part.

2.3. Characterization

The strength of these welds seams was determined in tensile lap shear tests following EN 1465 by dividing the breaking force by the weld area, which was evaluated from microscopic images after the tensile tests.

The geometry of the melt pools and the results from the gap bridging experiments were inspected by optical transmitted light microscopy using microtome sections with a thickness of 20 µm. The resulting geometry was compared with the results from the FE simulations.

3. Results

3.1. Scattering

Fig. 2 shows the portion of the radiation scattered out of the beam path of the spectrometer during the characterization of different polymers in the wavelength range of 810-2000 nm. Note that, apart from some amorphous polymers like Polycarbonate (PC) and polymethylmethacrylate (PMMA), where scattering can usually be neglected, v. Busse, 2005, optical properties of most polymers depend on the composition of the individual grade, the processing conditions and the resulting crystallinity. Therefore these results may not be transferable to different materials.

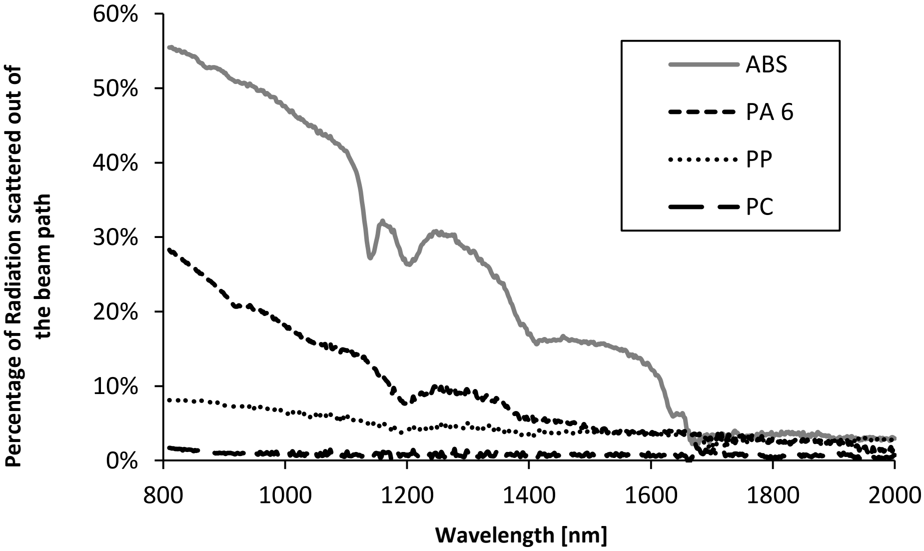


Fig. 2. Reduction of transmitted beam intensity due to scattering in 2 mm thick polymer samples;

As expected the influence of scattering is negligible for Polycarbonate (PC) and just a small amount of scattering occurs in the utilized Polypropylene (PP) grade, whereas the Polyamide 6 (PA 6) and Acrylonitrile Butadiene Styrene (ABS) samples, both show significant amounts of scattering.

With increasing wavelengths scattering decreases, which agrees to Rayleighs scattering law for small scattering centers, Fox, 2010. Above approximately 1700 nm the influence of scattering on the process can be neglected for these materials, making laser wavelengths of about 2 µm especially attractive for transmission welding with scattering transparent joining partners.

For the ABS material with a thickness of 2 mm, approximately 49 % of the initial intensity is scattered out of the beam path for the wavelength of 980 nm which is used in welding experiments, therefore a significantly higher demand of laser power can be expected to achieve good welding results compared to wavelengths above 1700 nm. Fig. 3 shows the resulting strengths of welds between ABS parts with different thicknesses of the transparent parts.

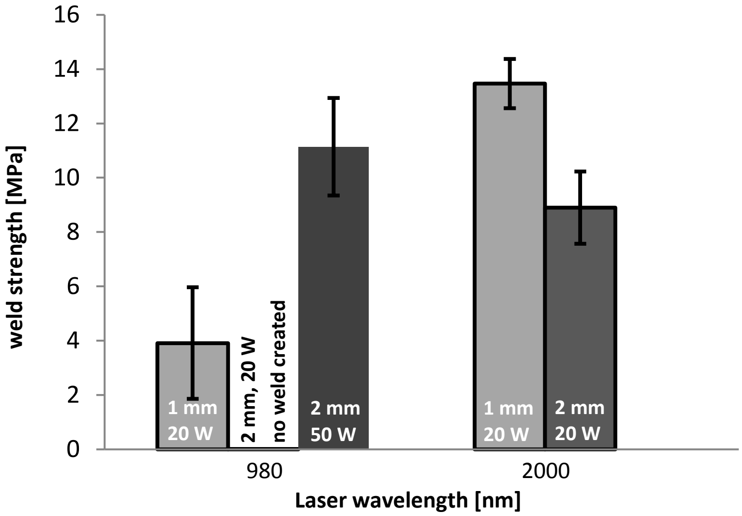


Fig. 3. Shear strength of quasi-simultaneous welds of ABS parts with different thickness of the transparent parts using conventional and adapted laser wavelength; Thickness of the transparent part and laser power are indicated in the bars; Sample size: n=4; Processing parameters: quasi-simultaneous welding, 30 irradiations at a frequency of 5 Hz, feed rate: 450 mm/s, initial beam diameter: 1.8 mm;

For the samples with a thickness of the transparent part of 1 mm, equal power levels could be used to join the two parts, but the weld strength was much higher for the samples welded with a laser wavelength of 2000 nm. With transparent parts with a thickness of 2 mm, the same power setting was no longer sufficient to create a weld. Even at 30 W no weld could be created and a power level of 40 W created welds with insufficient strength for handling. To achieve comparable weld strengths with the shorter wavelength of 980 nm, a much higher laser power of 50 W was required. For scattering materials the adapted laser wavelength of 2 µm clearly is advantageous in terms of efficiency and quality. Especially when small weld seam widths have to be achieved it features better control of the intensity distribution in the joining plane.

3.2. Melt pool geometry

Due to the concentrated heat generation at the surface of the absorbing part, typical weld seams created in laser transmission welding have a lens-shaped cross section as shown in Fig. 4. The strong temperature gradients are expected to lead to residual stresses during the cooldown phase, limiting the weld strength, Kittichai, 2008. Furthermore this heat concentration involves a risk of thermal degradation of the absorbent part, especially when heat conduction to the transparent part is affected by an air gap. Previous temperature field simulations showed, that by applying a laser wavelength of about 2.0 µm, which shows much higher absorption in the transparent part, the temperature distribution during quasi-simultaneous LTW can be modified, leading to reduced thermal gradients and reduced risk of overheating, Schkutow and Frick, 2016.

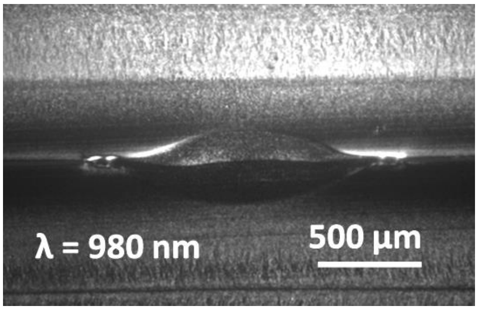


Fig. 4. Melt pool geometry created by quasi-simultaneous welding of PP using a wavelength of 980 nm;
Processing conditions: laser power: 20 W, irradiation frequency: 5 Hz, 30 irradiations, feed rate: 450 mm/s, beam diameter: 1,8 mm;

The resulting melt pool geometry can be altered from the common lens shaped to a drop- or egg-shaped cross section, with a much higher extension of the melt pool perpendicular to the joining plane. Fig. 5 shows the cross sections of welds seems created in PP and ABS respectively, using the 2.0 µm Tm-fiber laser confirming the simulative results.

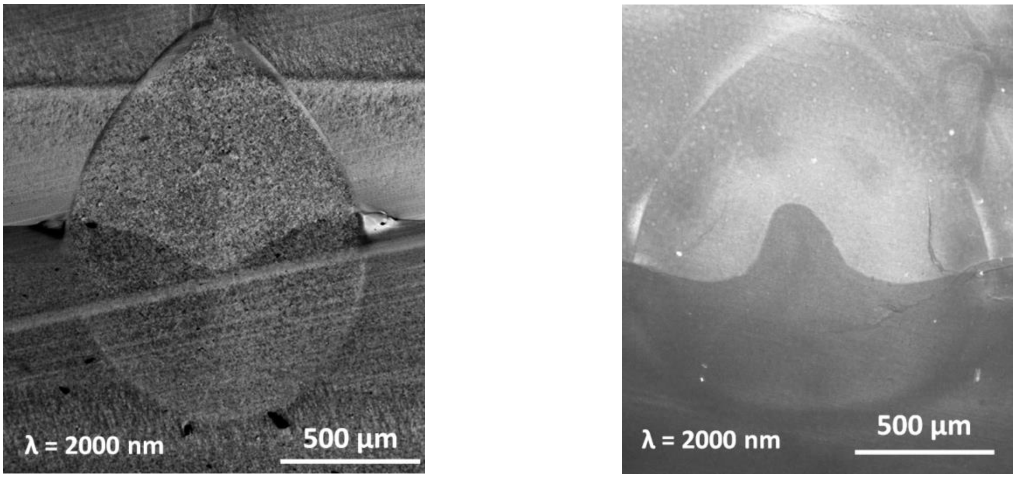


Fig. 5. Melt pool geometry created by quasi-simultaneous welding of PP (left) and ABS (right) using a wavelength of 2 µm;
Processing conditions: laser power: 30 W, irradiation frequency: 5 Hz, 30 irradiations, feed rate: 450 mm/s, beam diameter: 1.8 mm;

These weld seam geometries are created due to the higher intrinsic absorption in the transparent joining partner, the higher penetration depth of the radiation into the carbon black filled absorbent part and the relatively long interaction time between the materials and the radiation during the welding process. Lower residual stresses are expected due to the reduced thermal gradients caused by the widespread energy deposition. Furthermore the higher thermal expansion of both joining partners leads to increased joining pressures and an enhanced melt flow, indicated by the corrugated joining plane between the two parts. Both of these factors promote the intermixing and cross linking of the polymer chains, required for the weld formation, Acherjee et. al, 2012. Additionally, the increased size of the interface area can also beneficially influence the stability of the joint.

3.3. Gap bridging

Residual gaps between the parts, which could not be successfully closed by the clamping device, have to be bridged during the welding process by thermal expansion of the material to allow for thermal conduction between the parts and the wetting of the polymer surfaces, v. d. Ven and Erdman, 2007. The increased volume in which the heat is absorbed leads to a greater thermal expansion, especially of the transparent part when wavelengths of about 2 µm are used, which is beneficial for the gap bridging process. Additionally the more homogeneous temperature distribution between both joining partners is expected to reduce the risk of thermal degradation, since the heat accumulation at the surface of the absorbing part, caused by the insulating layer of air is much less pronounced.

To investigate the gap bridging capability of the adapted wavelength, samples with a defined gap created by glass spacers between the parts were welded. The welding results were compared with the results of a thermomechanical temperature field simulation, taking into account the wavelength dependent absorbance behavior, gap-size dependent heat transfer between the two parts to account for radiative and convective heat transfer and temperature dependent enthalpy to include phase change in the semi-crystalline material. Details on the simulation model, especially the modeling of the heat source can be found in Schkutow and Frick, 2016 and Schmailzl and Hierl, 2015.

Fig. 6. shows the temperature evolution and the deformation due to thermal expansion during quasi-simultaneous LTW of 2 mm thick PP samples. Material with a temperature above the melting temperature of 170°C is shown in gray color, representing the melt pool geometry.

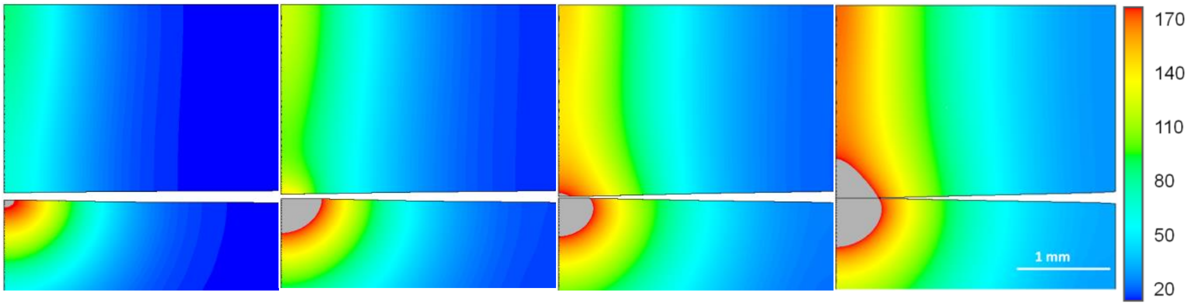
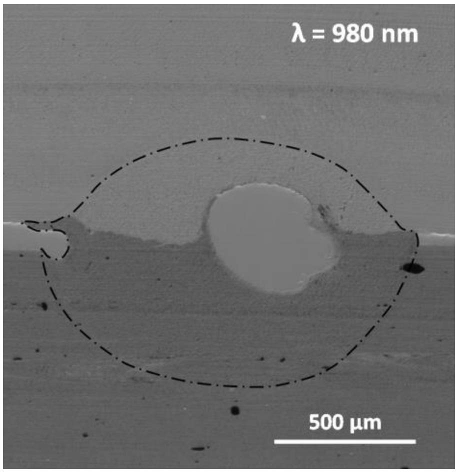


Fig. 6. Temperatures and deformed geometry during quasi-simultaneous welding of 2 mm thick PP; gap size: 130 µm, laser power: 20 W, beam diameter: 1.5 mm, wavelength: 2 µm, irradiation frequency: 5 Hz
Temperature distribution after:
a) 15 irradiations b) 30 irradiations c) 45 irradiations d) 60 irradiations

Temperature [°C]

Despite the relatively large gap, the absorbing joining partner is not excessively overheated before the gap is closed and the final melt pool develops a comparable, egg-like shape, as without a gap. This indicates a comparable weld seam quality for both cases, with and without a gap. The cooldown process was not included in the simulation, therefore the final weld seam geometry after cooldown was investigated experimentally, both for the conventional wavelength of 980 nm and the adapted wavelength of 2000 nm using the same gap size, laser power and irradiation frequency as in the simulation above. The beam diameter was 1.8 mm. As shown in Fig. 7. the gaps of 130 µm could be closed succesfully with both setups. To improve visibility of the heat affected zone a dot-and-dashed line was added indicating the boundaries of the area with modified crystallite structure after melting and resolidification.



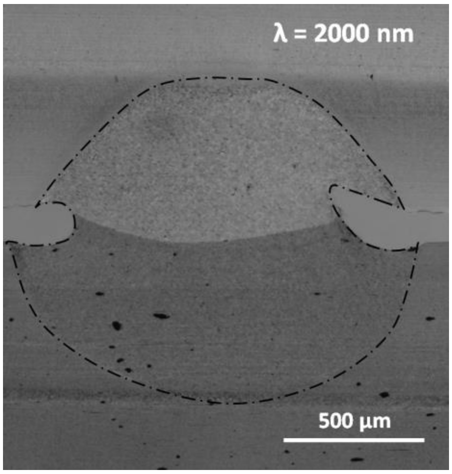


Fig. 7. (a) Melt pool geometry after quasisimultaneous welding of PP with a laser wavelength of 980 nm with a gap size of 130 µm;

Fig. 7. (b) Melt pool geometry after quasisimultaneous welding of PP with a laser wavelength of 2000 nm and gap size of 130 µm;

The weld created by the 980 nm laser shows a large void at the interface between both joining partners, indicating the formation of gaseous decomposition products due to overheating of the material. Furthermore, the cross sections of both weld seams show grooves at the interface, probably created by the shrinkage of the melt pool and the thermal contraction of the surrounding material during cooldown. In the case of the 980 nm wavelength, the generation of the gas cavity partly eliminates the formation of these grooves. Apart from these grooves, which reduce the effective weld seam width, the geometry of the weld seam created by the 2.0 µm laser shows good agreement to the simulated shape and no signs of thermal damaging, proving the beneficial gap-bridging capability of the welding process with laser wavelengths of about 2 µm.

4. Summary and Outlook

Based on the results of this study it can be asserted that LTW using alternative beam sources with laser wavelengths of about 2.0 µm not only enables the welding of similar polymers without absorbing additives, but can also improve welds between an absorbing and a transparent part. The reduced amount of scattering compared to usually applied wavelengths of about 1.0 µm enables better control of the intensity distribution in the joining plain and reduces the required laser power for the creation of the welds. The increased absorption of these wavelengths in most unmodified polymers enables a more homogeneous temperature distribution, expected to reduce residual stress levels. In quasi-simultaneous LTW the modified temperature fields can lead to novel melt pool geometries with egg-shaped cross sections of the weld seam and a much higher extension perpendicular to the joining plane, compared to the typical lens-shaped cross sections. These weld seams can improve the weld seam quality due to the increased thermal expansion, which especially improves the gap-bridging capability.

Future works will include the detailed analyses of the weld seam properties and an investigation of the processes during gap bridging with different materials and gap sizes. Additionally experiments will be carried out where the two different wavelengths will be combined, to further improve the potential to adjust the radiation specifically to the optical material properties and the geometry of the workpieces by changing the power distribution between the two lasers and the focusing conditions for both beams.

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