SIM PlanetQuest Spectral Calibration Development Unit beam combiner

Hong Tang
Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA, USA 91109

ABSTRACT

The beam combiner of an astronomical long-baseline interferometer combines the two beams of starlight to form white-light fringes. We describe beam combiner in the SIM PlanetQuest Spectral Calibration Development Unit (SCDU). In addition to forming white light fringes, the beam combiner provides other functions such as separating the light for guiding, fringe tracking, and science measurement. It is designed to function over the optical bandpass 450-950 nm. Coating design is critical to beam combiner as residual dispersion and mismatches affect the ability to accurately measure the position of stars of varying spectral types.

Key words: Beam combiner, dispersion, stellar interferometer, coatings

1. INTRODUCTION

The SIM PlanetQuest Spectral Calibration Development Unit (SCDU) is a white-light interferometer. [1] It is developed to demonstrate that an accuracy of 10 pm can be achieved in spectral calibration. The calibration involves taking out difference in optical delay for any two sources of different colors (simulating two stars). With a newly developed white light fringe model we have achieved 10 pm calibration for two sources of different colors in SCDU.[2,3]

The accuracy of the spectral calibration depends on the differential dispersion (phase vs. wavenumber) and differential wavefront error between the two arms of the interferometer. The differential dispersion and wavefront error are characteristics of the instrument. It depends on the design, manufacturing and alignment of the instrument.

The beam combiner is the central part of an interferometer. Light beams from the two arms combine at the combiner. If, by design, the optical systems in the two arms are identical, then the only contribution of design to the instrument dispersion is that of the combiner. The combiner in SCDU, as well as in SIM, also provides functions such as separating light for angle tracking (AT) and fringe tracking (FT) and science measurement.

Previous white light models assumes that the differential dispersion across the entire SIM Planet Quest pass band (450-950 nm) to be 30 nm.[4,5] If the dispersion is higher, it is more difficult to achieve an accuracy of picometer level in optical delay estimation. This imposes an upper bound of 60 nm on the dispersion of the design of the SCDU, which is a double-pass system.

In this paper, we describe combiner design considerations and trade-studies. We describe the design of SCDU combiner. This design meets the requirement of 60 nm peak-to-valley (P-V) dispersion double-pass across 450-950 nm band with phase compensation. We present the experimental measurements of the phase dispersion and show that they are in agreement with our model analysis.

2. COMBINER DESIGN CONSIDERATIONS

An asymmetric combiner design of a stellar interferometer is illustrated in Figure 1. Light from arm 1 of the interferometer is split at FT/AT 1 beamsplitter. The reflected portion is deflected by a mirror towards the main beamsplitter (MBS). We call this mirror the OMO (odd-man-out) mirror for there is not an equivalent one in Arm 2.

Similarly the reflected portion of light from FT/AT 2 in arm 2 is directed towards the MBS. A compensator is used to equalize the thickness of the bulk material in the two arms and to further reduce the residual dispersion due to coatings. Light from the two arms combine at the MBS and fringes can be observed at fringe trackers camera (FTC) A and B. The signal from FTC is used for fringe tracking and science measurements. The transmitted portion from the FT/AT beamsplitter is directed towards the angle tracker (AT). The function of the AT is to maintain the co-alignment of the light beams from arm 1 and arm 2.

At the MBS, light beam from either arm 1 or arm 2 is divided into the reflected and the transmitted beams. At port FTC A, the reflected portion of the beam 1 is combined with the transmitted portion of beam 2. Assume that beam 1 and beam 2 have the same electric field, E_0, before they enter the combiner. The electric field of beam 1 at FTC A is $(r_{AT/FT1} + r_{OMO} + r_{MBS})E_0$, where r is the amplitude reflection coefficient of the coating at each element. The electric field of beam 2 at FTC A is $(r_{AT/FT2} + t_{MBS})E_0$, where t is the amplitude transmission coefficient of the beamsplitter coating. The phase difference of the two interfering beams is then,

$$\begin{aligned}\Delta\phi_A(\lambda) &= \phi_{1A} - \phi_{2A} = r_{FT/AT1} + r_{OMO} + r_{MBS} - r_{FT/AT2} - t_{MBS} \\ &= (r_{MBS} - t_{MBS}) + r_{OMO} + (r_{FT/AT1} - r_{FT/AT2}),\end{aligned} \quad (1)$$

where l is the wavelength of the light.

For simplicity, we use r and t to represent the phase of the electrical field acquired at each coating encounter, omitting the amplitude part. The first term, $(r_{MBS} - t_{MBS})$ is the contribution of the MBS and r_{OMO} is the contribution of the OMO mirror. The third term, $(r_{AT/FT1} - r_{AT/FT2})$, is the contribution from the mismatch of coatings in the two FT/AT beamsplitters.

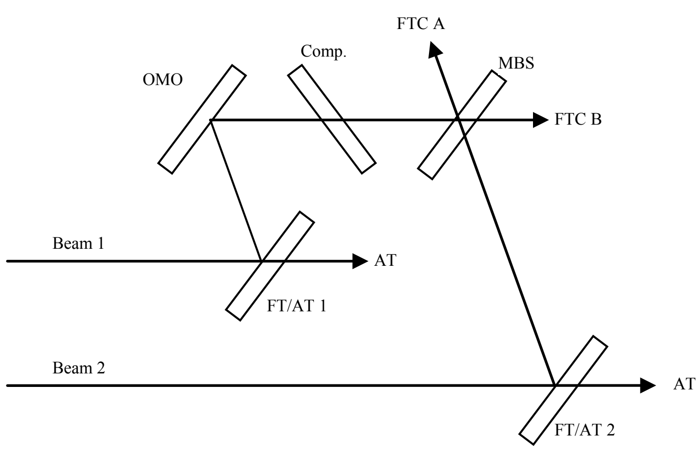

Figure 1. A combiner consists of FT/AT splitting functions. It typically has hundreds nanometers of dispersion in the band of 450 – 950 nm.

Differential phase dispersion is defined as the dependence on wavelength of the phase difference between beam 1 and beam 2. We express the phase dispersion in unit of waves (360 degrees = 1 wave at corresponding wavelength). We also express the phase dispersion in unit of nanometers, which is the number of waves times the corresponding wavelength.

To produce a high fringe visibility, a beamsplitter coating of $T/R \approx 50/50$ split ratio across the wavelength range of 450 – 950 nm would be prescribed for the MBS. The contribution of a coating to the phase of a beam of light upon reflection or transmission is a result of the interference of the electric fields reflected by or transmitted through all the layers. It is a complex multiple-beam interference phenomenon.[6] It can be deduced that the simpler the coating (fewer layers), the less dispersion there is. A broadband 50/50 beamsplitter coating generally requires 10+ layers. It has phase dispersion, i.e., *r* – *t*, in ~100 nm peak-to-valley in the passband of 450-950 nm. This is not acceptable for SCDU.

Theoretically, the coatings at FT/AT 1 and 2 are designed to be identical so that their contributions to the differential phase cancel out. In reality, there is mismatch in the two coatings. The differential phase dispersion due to the mismatch is in ~10 nm for a pair of 50/50 beamsplitters. This problem become a serious issue when the science team expressed desire to have more than 50% of light for the FTC and hence the science measurements. Because the light for FTC is reflected by beamsplitters FT/AT 1 and FT/AT 2, the coating design would be much more complex if higher than 50% reflectance is required. Our analysis shows that if 80% of light is reflected for the FTC (R/T = 80/20 for FT/AT), the coating of FT/AT beamsplitter requires 40+ layers. Assume thicknesses in FT/AT 1 differ from that of the FT/AT 2 by merely 0.2%. The phase dispersion due to the mismatch, i.e. the third term in Equation (1), is increased to ~100 nm. In order to achieve a phase dispersion of < 60 nm for SCDU, other combiner architecture has to be considered.

To significantly reduce the phase dispersion, a symmetric beam combiner is proposed.[7] As it is mentioned above, in our combiner system, there are two additional beamsplitters in arms 1 and 2 that are used to split a portion of light to the angle tracker. We can use these two beamsplitters and the main beamsplitter to form a symmetric combiner system (Figure 2). In the symmetric combiner, beams 1 and 2 that reach port A encounter the same number of reflection by beamsplitters and same number of transmission through beamsplitters and bulk material. The key assumptions are that all the beamsplitter and anti-reflection (AR) coatings are identical, all bulk substrates are of the same thickness and the angle of incidence (AOI) is the same for every optic. To reach FTC A, beam 1 transmits through BS 1 and is reflected by MBS. Beam 2 is reflected by BS 2 and transmits through MBS. The differential phase at FTC A of beams 1 and 2 is then,

$$\Delta\phi_A(\lambda) = \phi_{1A} - \phi_{2A} = t_{BS1}r_{MBS} - r_{BS2}t_{MBS} = 0.$$

Practically, there is always some difference in the layer thickness among the three beamsplitters. Sophisticated planetary systems in a coating chamber and well calibrated process can reduce the non-uniformity from optic-to-optic to nearly 0.1% of the total layer thickness.[8] To simulate the effects of coating mismatch, the beamsplitter coating MBS is perturbed such that the thicknesses of all layers are scaled by 1.001 to simulate the coating mismatch of 0.1%. The

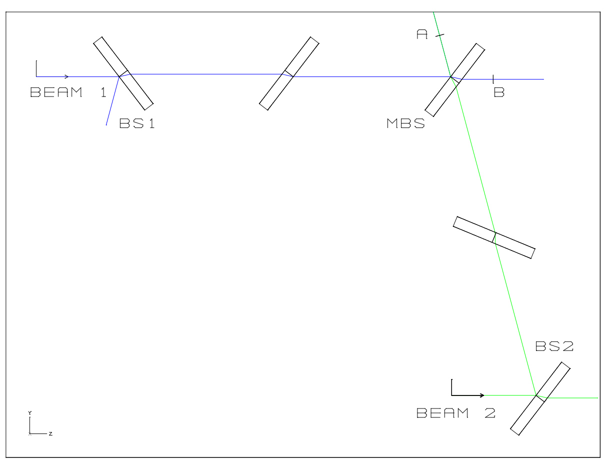

Figure 2. The layout of a symmetric beam combiner. It consists of three beamsplitters and two compensators. The two beams at port A have zero phase difference.

coatings at BS1 and BS2 stay unchanged. The phase of beam 1 at port A is $\phi_1 = t + r_{1001}$ and the phase of beam 2 at port

A is $\phi_2 = r + t_{1001}$, where r_{1001} and t_{1001} are phases acquired by the light beams when they are reflected off and transmit through the 1.001x scaled MBS coating. We use an R = 50% BS coating with more than 10 layers. The phase difference is calculated and plotted in Figure 3. The dispersion of the phase difference at port A is increased from zero for a perfect system to 3 nm peak-to-valley. In reality even with the most sophisticated coating system, it is difficult to fabricate coatings onto two beamsplitter substrate such that the layer-to-layer matching is better than 0.5%. The achievable phase dispersion in the symmetric combiner would be at 15 nm level P-V.

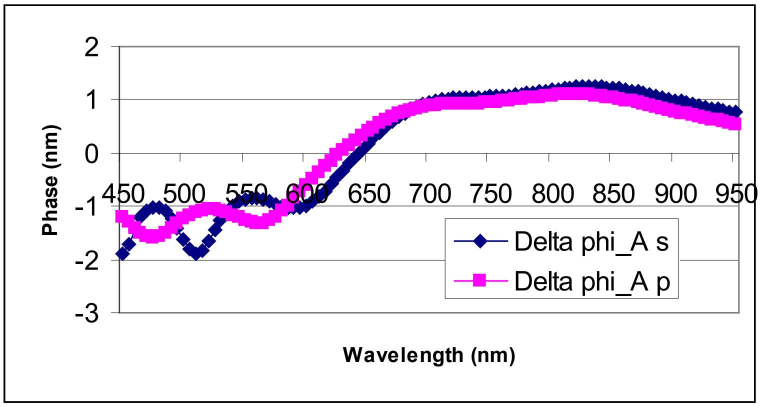

Figure 3. The dispersion of the phase difference at port A for the symmetric combiner with 50/50 beamsplitters when the MBS coating is scaled by 1.001. The angle of incidence is 45˚. The two curves are for s and p polarizations respectively.

The symmetric combiner design and tolerance meets the 60 nm phase dispersion requirements for SCDU. However, the symmetry requires that the FT/AT split ratio to be strictly 50/50. It is always desirable to reserve the option and capability of having more photons for FTC and science measurements. This turns our attention to asymmetric combiners.

3. THE SCDU COMBINER

The design goals for a SCDU combiner become clearer. They are to design a combiner that has

1. A double-pass dispersion less than 60 nm in 450 – 950 nm or a single-pass dispersion less than 30 nm.
2. The flexibility of splitting more than 50% of light to the FTC.

The two major contributors to the phase dispersion in the asymmetric combiner, shown in Figure 1, are the coating of the main beamsplitter (r - t) and the mismatch of the coatings in the two FT/AT beamsplitters. Design and trade studies are carried out to understand the challenges of reducing the dispersion in combiners.[9] We examined the effects of the angle of incidence by using AOI of 20, 37.5 and 45 degrees. We find out that the retardance in the combiner, defined as the difference in phases of s and p polarizations is of ~10 nm for coatings at AOI of 37.5 and 45 degrees. To have less amount of retardance we must choose a small AOI in our design.

We then examine the phase dispersion of the combiner with the simplest MBS coating, a two-layer coating. The phase dispersion is plotted in Figure 4. The P-V dispersion for either s or p polarization is 12 nm (single-pass). This 2-layer coating has T/R ratio of 80/20. The photon efficiency, $4TR$, of fringes formed in this combiner is only 0.6, much lower than what is acceptable. We gradually increase the number of layers for the MBS in our study. The photon efficiency improves as the T/R ratio becomes much closer to unity from 80/20 for the 2-layer to 55/45 for an 8-layer coating. The phase dispersion increases significantly for the MBS with 8-layers, as shown in Figure 5. It is 12 nm for 2-layer coating and 70 nm for 8-layer coating. It is clear that the 5-layer MBS coating is the choice for meeting the requirements on phase dispersion and having enough photon efficiency. It has 16 nm P-V dispersion, which meets the requirement of single-pass dispersion 30 nm. The coating has a *T*/*R* ration of 60/40 in the wavelength range 470 – 850 nm, which gives a photn efficiency of 0.96. The *T*/*R* ratio tapers off to 75/25 near the two extremes of the required wavelength range.

For the two FT/AT beamsplitters, the coating is much simpler if the transmittance is greater than the reflectance. For instance, an *R*/*T*=30/70 coating is much simpler than an *R*/*T*=70/30 one. This is due to the complexity in designing and making a broadband non-metallic high-reflectance coating.

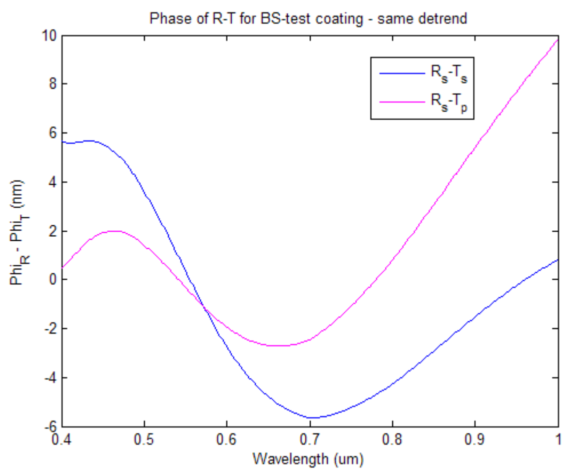

Figure 4. The (single-pass) phase dispersion of the MBS with a 2-layer coating. The P-V value is 12 nm for either s or p polarization.

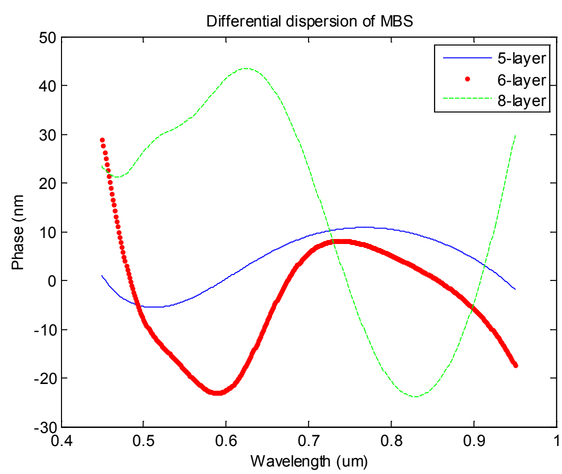

Figure 5. The phase dispersion of the MBS with 5, 6 and 8 layer coatings. It is single-pass.

We consider a new architecture for the combiner in SCDU. It is presented in Figure 6. In the new design, light that transmits through the FT/AT beamsplitters is used for fringe tracking and hence the science measurements. This significantly reduces the amount of phase dispersion due to the coating mismatch of FT/AT 1 and FT/AT 2.

The SCDU is a double pass system. White light is injected into the system through the FTC_A at the MBS. The light beam is separated into two paths, beam 1 and beam 2. Both beams are retro-reflected by two mirrors, one in each arm. Upon returning to the combiner, a percentage of light in both beams is reflected towards the angel tracker (AT) by BS 1 and BS 2, respectively. The transmitted light is directed towards the MBS and interference fringes are formed at FTC_B. We choose an angle of incidence of 22.5°. The reason it is not 20° is that the reflected beam is at an angle of 45°, an angle at which more auxiliary alignment optics are available. It is difficult to reduce the AOI below 20° for there is little space for optical and opto-mechanical layout.

Differential phase at FTC_B for a double-pass through the combiner with WL source at FTC_A can be simplified and express as

$$\Delta\phi_B(\lambda) = \phi_{1B} - \phi_{2B} = 2[\underline{(r_{MBS} - t_{MBS})} + \underline{r_{OMO}} + \underline{(t_{FT/AT1} - t_{FT/AT2})} + \underline{\Delta t}],$$

The contributors to the phase dispersion are the MBS, the OMO mirror and the mismatch of the two FT/AT beamsplitters (BS1 and BS2). The additional term, Δt, represents the difference in total thickness of bulk (substrate) material that beam 1 and beam 2 encounter before combining.

The dispersion in bulk material is mostly quadratic with respect to wavelength. The MBS coating consists of 5-layers. Its phase dispersion is mostly of cubic form. The dispersion of the OMO is also mostly quadratic. Thus, the quadratic term in the dispersion from the MBS and OMO can be compensated (reduced) by introducing additional thickness of bulk material in either arm 1 or arm 2. Balasubramanian demonstrated that the overcoat thickness of aluminum mirror coating can be used to compensate the retardance in the TPF-C (Terrestrial Planet Finder Coronagraph) optics.[10] By applying a similar technique, dispersion compensation in the combiner can be further improved with proper thickness of the overcoat layer of the metallic mirror coating for OMO. To calculate the total dispersion in the SCDU combiner, phases from all the coatings are summed. The linear term in the total dispersion is minimized by adjusting the optical delay in one of the two arms. The parabolic term is minimized by choosing a proper thickness for the overcoat of OMO and tilting the compensator plate. The residual dispersion is less than 60 nm (double-pass) as presented in Figure 7.

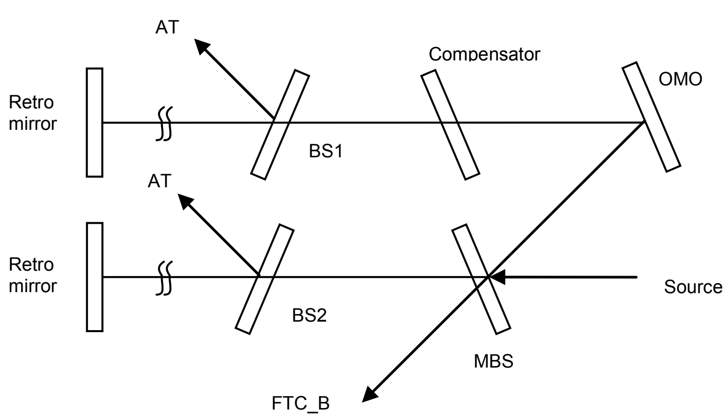

Figure 6. A new architecture for the asymmetric combiner. The light for FTC transmits through BS1 and BS2. This allows much simpler coating for BS1 and BS2 and hence much more tolerant to the mismatch of coatings deposition errors in BS1 and BS2. The SCDU is a double-pass system. White light source is injected at FTC_A. Fringe detection is at FTC_B.

All the back sides of the beamsplitters in the SCDU combiner are coated with the same broadband antireflection (BBAR) coating. Assume that both sides of the compensator plate are also coated with BBAR. We count the number of BBAR coatings in each arm of the combiner. We find out that there is one extra BBAR in arm 1 where the compensator plate is. To balance the number of BBAR in both arms we choose to apply a single layer MgF_2 antireflection coating to one side of the compensator. The phase dispersion of the single layer MgF_2 is negligible.

At the initial phase of SCDU operations, we conduct the phase dispersion measurements of the SCDU system. The SCDU system consists of the combiner and five addition mirrors in each arm.[1] We adjust the optical delay in one arm to minimize the group delay, i.e. the linear term in the phase dispersion. We tilt the compensator to minimize the quadratic term in the system dispersion so that the P-V dispersion of the system is minimized. The results of our measurements of the SCDU system dispersion are plotted in Figure 8. For comparison the theoretical dispersion curves from our combiner model are also plotted. The P-V value of the measurement (average polarization) is 58 nm for the entire SCDU system. The P-V dispersion of the design (average polarization) is 52 nm. We consider the measurements and the model in good agreement if we take into consideration of coating layer thickness errors. Coatings thickness measurements by the manufacturer reveal that the layer thickness error is more than the 2% specified for the beamsplitters. We estimate the coating error in the OMO to be 5% based on the reports of the deposition trials from the manufacturer. We estimate that the coatings of the five addition mirrors in one arm mismatch the coatings of their counterparts in the other arm by 5%.

4. CONCLUSION

We have designed a beam combiner that has less than 60 nm double-pass dispersion in the 450 – 950 nm passband. We have measured a P-V dispersion of 58 nm for average polarization in the entire SCDU system. The SCDU system includes five more mirrors in each arm in addition to the combiner. Accounting for all the tolerances in coatings of combiner and the five additional mirror pairs, the measurements are considered to be in good agreement with the model.

To accomplish the design of SCDU combiner with low dispersion, we use transmitted light from the FT/AT beamsplitters for the science measurements. The phase dispersion from the mismatch of the two FT/AT beamsplitters for transmitted light is much smaller. We use simple coatings and use matched coatings in both arms. Furthermore, we use the overcoat thickness and the compensator to reduce the total phase dispersion in the combiner.

The combiner design is an important step toward our goal for the SCDU, that is, to demonstrate that an accuracy of 10 pm can be achieved in spectral calibration. This combiner design has been incorporated into SIM PlanetQuest’s ABC (Astronomical Beam Combiner).

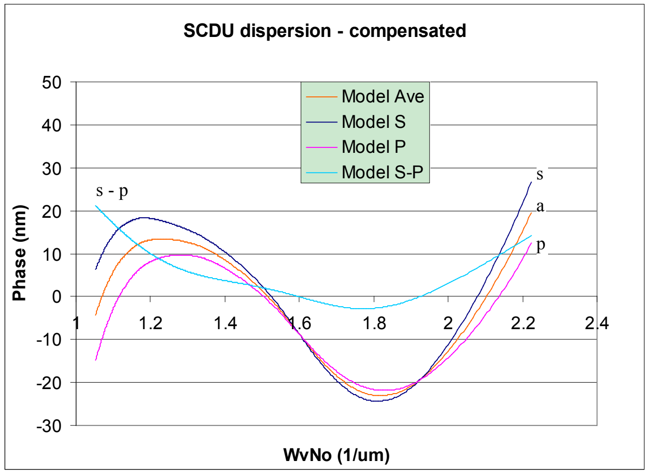

Figure 7. The phase dispersion of the compensated SCDU combiner. The horizontal axis is the wavenumber in μm^{-1}. The four curves are phases of the s and p polarizations, the average and the difference of s and p.

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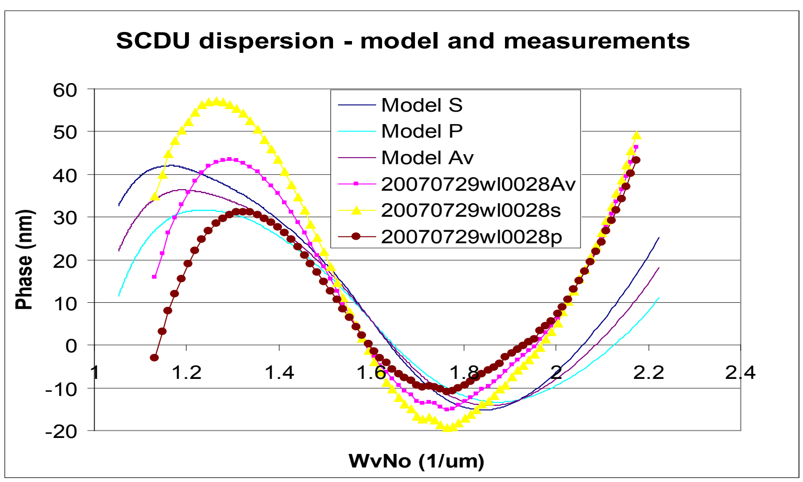

Figure 8. Phase dispersion measurement of the SCDU system and phase dispersion of the SCDU combiner model. The P-V of the measurement for average polarization is 58 nm. The P-V of the design for average polarization is 52 nm.

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