Comparison of Different Polymeric Multimode Star Couplers for Backplane Optical Interconnect

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***Abstract*— This paper describes a comparison of three types of 8 × 8 multimode star couplers made in polymeric multimode waveguides. Their geometry was designed with a ray tracing tool. Measurements show low loss for all designs, but a symmetrical design, based on a tree of Y-junctions yields the best uniformity.**

I. Introduction

OPTICAL INTERCONNECT is very promising for signal transport in advanced digital systems with high data rates at the board and backplane level. One of the aims of the ESPRIT III project HOLICS (Hierarchical Optical Interconnects for Computer Systems), is the interconnection of N boards by an optical backplane. In the star coupler topology of Fig. 1, each board can transmit a signal to all N boards and only one board can transmit at a time. The output from a laser diode on the board is coupled in the backplane, where it is guided to the $N \times N$ star coupler. This star coupler distributes the light from the input guide to all output guides. The signal in these guides is then detected by a photodiode on each board. Multimode polymeric waveguide boards offer an interesting solution for such interconnect problems because they give the opportunity for a more complex functionality than is possible with point to point links. Also, they allow mass production on large surfaces, the material is flexible and can be used in an acceptable temperature range.

Multimode waveguides have the advantage of relaxed coupling conditions. The large modal volume allows large lateral and/or angular misalignment. Both the size of the laser facet and the divergence angle of the laser beam are small as compared to the waveguide facet and waveguide numerical aperture. Related to the relaxed coupling conditions however is the problem of modal noise. The light coupled from a laser diode will not excite all modes with equal power. There will be a certain modal distribution that strongly depends on the coupling conditions. This uncertainty in modal content effects the performance of multimode waveguide elements (bends, junctions, ...). Therefore, the design of multimode waveguide elements is often more difficult than that of single mode structures.

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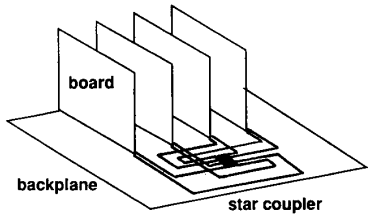

Fig. 1. Boards interconnected with an optical backplane in a star coupler topology.

This paper discusses the design and performance of three realized 8 × 8 star couplers. The structures have been fabricated by DuPont using their Polyguide™ integrated optics system [1]. The waveguides have a rectangular core cross-section. The nominal core area of the guides is 45 × 45 μm^2 (the nominal guide width is 45 μm). The waveguides are step index guides, the refractive index of the core n_{co} is 1.53 and 1.5 in the cladding index n_{cl}. The numerical aperture is 0.3 and the number of modes M at a wavelength of 1 μm, about 1500 [2].

II. The Modeling of the Star Couplers

The question arises how to model these highly multimode waveguides. For either single mode or free space problems a lot of algorithms have been developed. For problems where there are only a few modes, one can use theories based on modes. The highly multimodal situation is somewhere in between the single mode case and the free space case, but since we have a quasi continuum of modes it is closer to the free space case where we have a continuum of modes (plane waves).

Techniques where all the modes are traced through the structure are only useful if one can determine the coupling of power between the modes for z-variant structures as in the coupled mode theory. This will be a difficult task, and even if we could do it, the numerical implementation would ask for large computing times since the number of modes is so large. One can argue to use the beam propagation method (BPM). A disadvantage of this method is that the propagation direction must be the same for all waveguides of the structure. This is no restriction for the star couplers of this paper, but more general structures that appear on the boards cannot be modeled with BPM. Furthermore, BPM requires small propagation steps. This leads to time consuming calculations for structures with a length of several mm to a few cm, as is the case for the multimode polymer waveguide structures.

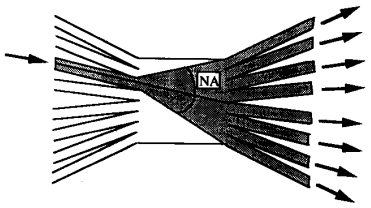

Fig. 2. Short star coupler based on imaging. NA is the numerical aperture of the guides.

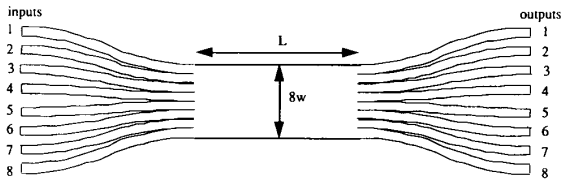

Fig. 3. Mixer rod star coupler. L and $8w$ are the length and width of the central mixing section.

We propose to use rays which can be seen as local plane waves. Ray tracing is a widely used technique in free space problems, but also used in waveguide problems [3], [4]. Its major disadvantage is that wave effects as interference and diffraction are neglected. The couplers were modeled with a 3-D ray tracing tool [5], developed specifically for this task. It includes the effects of (polarization dependent) reflection and transmission.

In this ray picture, different modes can be associated with different ray angles [6]. More oblique rays (rays making a larger angle with the guide axis) correspond with higher order modes. A uniform modal distribution corresponds with a uniform distribution of ray angles within the numerical aperture. In this paper, all simulations where done with 2-D ray-tracing. Hereby we excite all possible rays with equal probability in a plane parallel with the substrate. The rays are located in the core, and the ray angles are within the numerical aperture. In [7] we argued that for waveguides with square cross-section this will make only a marginal difference as compared with the 3-D result, where all possible rays are excited within the core and the numerical aperture of the guide, if the structure does not vary in the direction perpendicular to the substrate.

III. Star Coupler Designs

A. Introduction

The purpose of an $N \times N$ star coupler is to couple light from one of its N input guides to all the N output guides uniformly (i.e., equal power in all output guides). We assume that the power is uniformly distributed in the excited input, i.e., the power or ray distribution is constant over the waveguide core and is constant within the numerical aperture of the guide.

To obtain very short structures, a star coupler has been designed where the light of the input guide is projected on the array of output guides. The principle of this design is shown in Fig. 2. The guides join the central section such that the light coming from them illuminates all the output guides with approximately the same power. The output guides leave the central section so that the power is coupled efficiently. It is obvious that this design is sensitive to variations in parameters.

Another disadvantage of this design is that the power distribution needs to be perfectly uniform within the numerical aperture to obtain uniform coupling to output guides. However, due to modal noise this is not certain. Since we make use of the large modal volume of multimode waveguides to relax the coupling conditions, it is far from evident that all angles within the numerical aperture will be excited equally. A way to cope with this problem is the use of mode scramblers, that randomize ray distributions. However, they add loss to the structure.

It is therefore necessary to look for designs that do not depend so strongly on the modal excitation. If light is coupled in from the input guide to a mixing section where it spreads uniformly over the core of that mixing section, the light can be coupled from the mixing section to all N output guides. Thus, a uniform distribution of the power over the output guides is obtained. We designed three 8×8 star couplers based on that idea, one with a central mixing rod, where combining and splitting is done in a single step, and two based on a tree like structure where the guides are split and combined two by two. These designs are expected to be insensitive to small variations in the parameters. For the modeling we will still assume that the power distributions are uniform.

In all designs we use S-bends. These are made up of two circular sections with opposite curvature. Earlier work on bends [7] showed that the loss of S-bends with 45 μm width is acceptable (less then 0.5 dB) for a radius $R > 16$ mm. The S-bends used in the designs have therefore $R > 16$ mm.Furthermore, we found that a uniform power distribution is still uniform after propagation through an S-bend with $R > 8$ mm. This is important for guides that join a mixing section with an S-bend. If the guide is excited with a uniform power distribution, the power distribution will also be uniform when it couples to the mixing section.

B. Mixer Rod Star Couplers

In this design, the individual input and output guides join the central mixing section parallel to its axis (see Fig. 3). The offset between the guides is provided by S-bends with $R > 16$ mm. The width w of the input and output guides is 45 μm and the pitch between them 150 μm.

To determine its length L, the spreading of light in the central mixing section was modeled. Fig. 4 shows the power in the individual outputs 1–8 and the spread of power at the 8 outputs as a function of the mixer length when input 1 is excited uniformly. Losses due to different curvature R of the S-bend are neglected in this calculation. The splitting is uniform if L is larger than a few cm. Fig. 5 gives the results when input 4 is excited uniformly. In this case, the same uniformity is obtained for shorter lengths L. The results for inputs 2 and 3 can be expected to be in between those for inputs 1 and 4. If we focus on the results for input 1, which

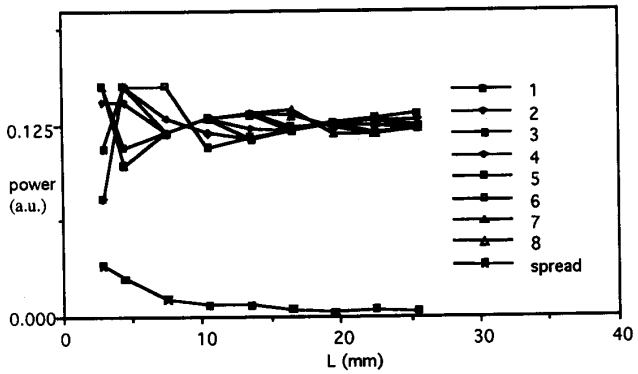

Fig. 4. Simulation of the power in the 8 outputs of the mixer rod star coupler as a function of the mixer length L. The spread (standard deviation) of the power at the outputs is a measure for the uniformity of the star coupler. Input 1 is excited with a uniform power distribution.

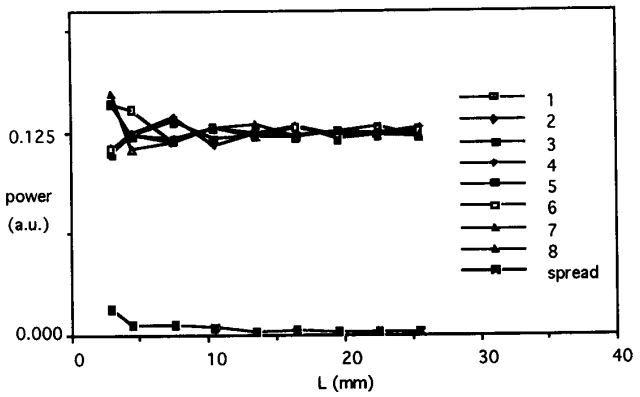

Fig. 5. Simulation of the power in the 8 outputs of the mixer rod star coupler as a function of the mixer length L. The spread (standard deviation) of the power at the outputs is a measure for the uniformity of the star coupler. Input 4 is excited with a uniform power distribution.

is the worst case, we conclude that the central mixing section must have a length L larger than 20 mm. This star coupler has been made for $L = 20$, 30, and 40 mm. The length of the S-bends is 5 mm. This brings the total length to 30, 40, and 50 mm.

C. Symmetric Tree Star Coupler

The different interconnection paths in the mixer rod star coupler have different total bending and as a result different losses. The uniformity of power at the outputs of the coupler will be degraded by this. In the design of Fig. 6, the 8 input guides are combined two by two with symmetrical Y-junctions to a central mixing section and are split out in the same way. The total bending of all interconnections is equal. The geometry of the junctions and the length of the mixing sections between them, has to be determined so that we have a star coupler with low loss and good uniformity.

Fig. 7 shows three options for the geometry of the Y-junctions. The waveguide with width w can be split into two guides with the same width w (Fig. 7 (a)) or with width $w/2$ (Fig. 7 (b)). The S-bends give the junctions a certain pitch. Another possibility is a split to guides with width $w/2$, but leaving the main guide under an angle β (see Fig. 7 (c)).

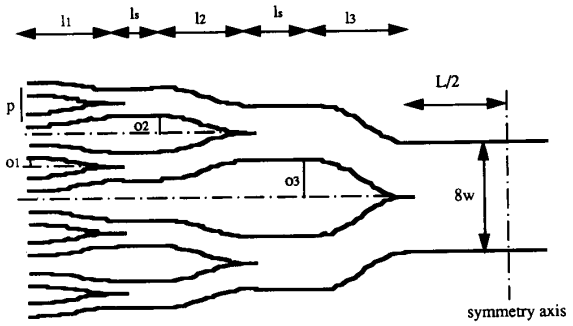

Fig. 6. Symmetric tree star coupler. Only the first half is shown. L is the length of the central mixing section. l_1, l_2, and l_3 are the lengths of the S-bend sections and o_1, o_2, and o_3 their offset. There are straight guides with length l_s between the Y-junctions. The width of the input guides is w and their pitch p.

Measurements and modeling results show lower losses for the design of Fig. 7(b) as compared to (a) and (c) if the length and pitch of the splitter are kept constant. Thus, the Y-junctions used in the design of the symmetric tree star coupler have the geometry of Fig. 7(b). The values used for R are 16 and 25 mm.

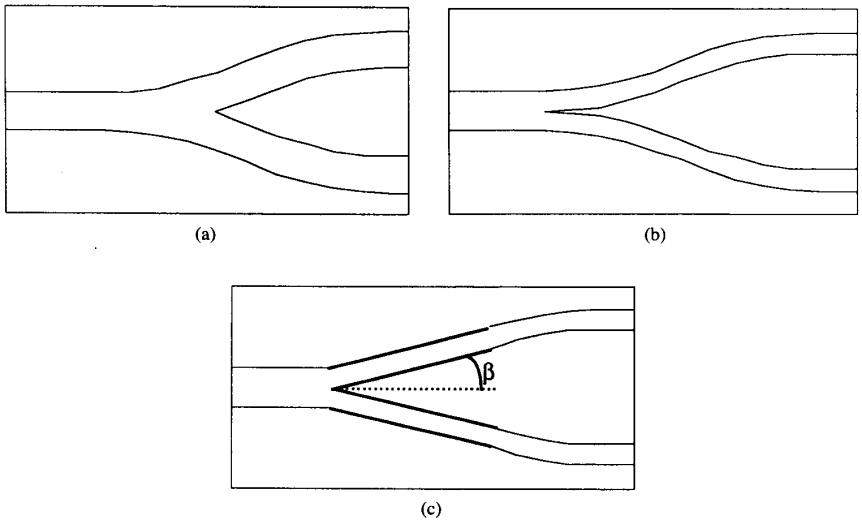

Fig. 7. Three types of Y-junctions, (a) S-bend split to full width arms, (b) S-bend split to half width arms, (c) Angular split.

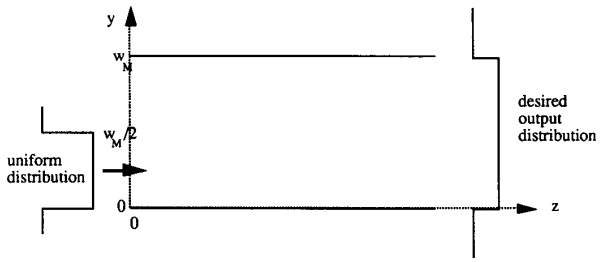

Fig. 8. A mixing section of the tree star couplers. For an appropriate choice of the length z, a uniform excitation in half of the core will be transformed to a uniform distribution over the entire core.

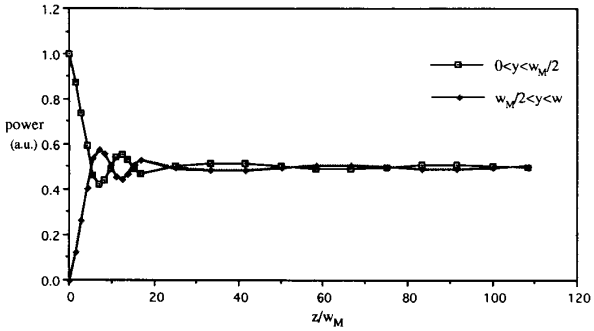

Fig. 9. Simulation of the power in the core of the mixing section (see Fig. 8) versus z/w_M.

When light is coupled into one of the inputs, the sections (with lengths l_2, l_3 and L) of the combining half of the star coupler must randomize a distribution that excites only half of the core with a uniform spatial distribution, to a distribution that fills the core uniformly (see Fig. 8). Since R is large, we can treat all sections as straight guides. The distribution is considered uniform in a cross-section of the guide with width w_M if the power in $0 < y < w_M/2$ equals the power in $w_M/2 < y < w_M$. Fig. 9 gives the power in these two parts of the core cross-section as a function of z/w_M, obtained with the modeling tool. z scales with w, due to the geometric scaling of ray paths. For z/w_M between 10 and 20, the distribution of power is already satisfying. The power is equally distributed if $z/w_M > 20$. For $z/w_M = 20$ we find $L = 7,2$ mm ≈ 1 cm as length of the central mixing section ($w_M = 360\ \mu$m).

The lengths l_2 and l_3 of the other mixing sections have to fulfil $z/w_M > 20$ as well. For large R, the length l of an S-bend with offset o can be approximated as:

$$l \approx 2\sqrt{o \cdot R}. \tag{3}$$

l_2 and l_3 can be found from (3) and Fig. 6:

$$\begin{aligned} o_1 &= \tfrac{1}{2}(p - w) = \tfrac{1}{2}(150 - 45)\ \mu\text{m} = 52.5\,\mu\text{m} \\ o_2 &= p - w = 2o_1 \\ o_3 &= 2(p - w) = 4o_1 \qquad (4) \\ l_1 &\approx 2\sqrt{o_1 \cdot R} \\ l_2 &\approx 2\sqrt{o_2 \cdot R} = \sqrt{2}l_1 \\ l_3 &\approx 2\sqrt{o_3 \cdot R} = 2l_1. \qquad (5) \end{aligned}$$

For $R = 16$ mm we find $l_2 = 2.6$ mm and $l_3 = 3.7$ mm. This leads to the values 29 and 20 for z/w_M respectively. Thus $z/w_M > 20$ for all mixing sections. If $R = 25$ mm, the uniformity will improve.

To further improve the uniformity, straight guides with length $l_s = 2$ mm are added between the S-bends and the Y-junctions. The total length of the star coupler is 38 mm for $R = 16$ mm and 42 mm for $R = 25$ mm.

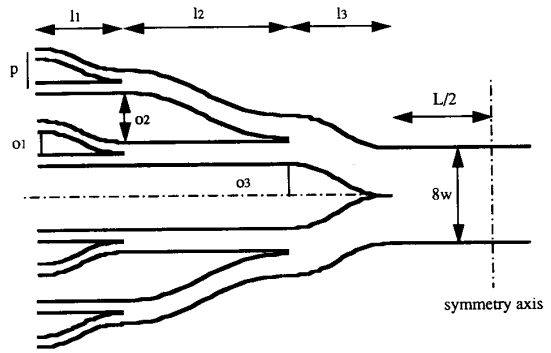

Fig. 10. Asymmetric tree star coupler. Only the first half is shown. L is the length of the central mixing section. l_1, l_2, and l_3 are the lengths of the S-bend sections and o_1, o_2, and o_3 their offset. The width of the input guides is w and their pitch p.

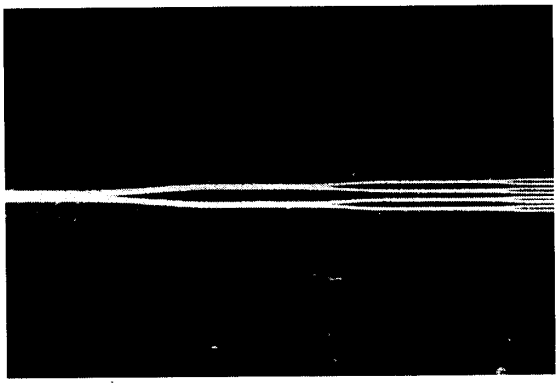

Fig. 12. This photograph shows the splitting section of the symmetric tree star coupler ($R = 25$ mm) when He–Ne laser light is coupled into input 1.

Fig. 11. Photograph of the polymer waveguide sample, containing the realized structures. The size of the sample is 70 mm × 25 mm.

D. Asymmetric Tree Star Coupler

The lengths of both the mixer rod and the symmetric tree star couplers are rather long. Shorter structures can be obtained with the asymmetric design of Fig. 10. The number of S-bends is minimized and the straight sections between S-bends and Y-junctions are left out. The Y-junctions split the guides to half the width, but they are asymmetrical, only one of the branches is an S-bend. The values used for R (radius of the bent sections) are 16 and 25 mm, and for the central section we take $L = 1$ cm, as with the symmetrical tree.

The lengths l_2 and l_3 of the other mixing sections can be found from Fig. 10 and (3):

$$\begin{aligned} o_1 &= p - w = (150 - 45)\,\mu\text{m} = 105\,\mu\text{m} \\ o_2 &= 2(p - w) = 2o_1 \\ o_3 &= \frac{1}{2}(p - w) = 2o_1 \end{aligned} \tag{6}$$

$$\begin{aligned} l_1 &\approx 2\sqrt{o_1 \cdot R} \\ l_2 &\approx 2\sqrt{o_2 \cdot R} = \sqrt{2}l_1 \\ l_3 &\approx 2\sqrt{o_3 \cdot R} = \frac{1}{\sqrt{2}}l_1. \end{aligned} \tag{7}$$

For $R = 16$ mm we find $l_2 \approx 3.7$ mm and $l_3 \approx 1.8$ mm. This leads to the values 41 and 10 for z/w respectively. The value $z/w = 10$ for l_3 is rather low, but Fig. 9 shows that the distribution of power is already acceptable about that point. The situation improves for $R = 25$ mm there we find z/w values 51 and 13 for l_2 and l_3 respectively. Thus, the lengths l_2 and l_3 of the mixing sections are long enough. The total length of the asymmetric tree star coupler is 26 mm for $R = 16$ mm and 30 mm for $R = 25$ mm. These designs are about 30% smaller than the symmetrical designs, for the same value of R.

IV. Experimental Results

All structures designed in Section III were realized with the polymer waveguide technology Polyguide™ of DuPont [1]. The polymer waveguide sample with the realized structures on is shown in Fig. 11. Fig. 12 is a photograph of the splitting part of the symmetric tree star coupler ($R = 25$ mm) when light from a He–Ne laser is coupled into input 1. The splitting to the 8 output guides can be seen clearly.

Measurements were done to determine the losses and uniformity of the realized structures. We transformed the beam of a YLF laser at 1.047 μm to a point source with $NA = 0.35$. This is the best match with the numerical aperture of the waveguide. For the mixer rod star couplers and the symmetric tree star couplers, we coupled this point source at inputs 1, 4, and 6 (the inputs are numbered as in Fig. 3). In the asymmetric tree structures we coupled in at all 8 inputs. The power at all 8 outputs has been measured for each excitation. When a uniform point source is coupled in a multimode step index waveguide, the light will after soon spread to a uniform power distribution over the core and within the numerical aperture. This is analogous to the mixing in the mixer rod star coupler. For guides with a width of 45 μm, the power is uniform after a length of a few mm. The length of the guides on the sample, before they combine in the star coupler, is several cm. Therefore, a uniform power distribution will be coupled in the star couplers when the input guides are excited with the uniform point source.

TABLE I
SUMMARY OF RESULTS FOR THE STAR COUPLERS

TYPE	parameters	total length (mm)	max. excess loss (dB)	average excess loss (dB)	uniformity (dB)
mixer rod	L=2 cm	30	-2.43	-0.24	1.37
mixer rod	L=3 cm	40	-3.65	-0.71	1.48
mixer rod	L=4 cm	50	-2.57	-0.34	1.42
symm. tree	R=16 mm	38	-2.36	-1.73	0.54
symm. tree	R=25 mm	42	-0.80	-0.16	0.40
asymm. tree	R=16 mm	26	-4.13	-1.57	1.23
asymm. tree	R=25 mm	30	-2.64	-0.70	0.97

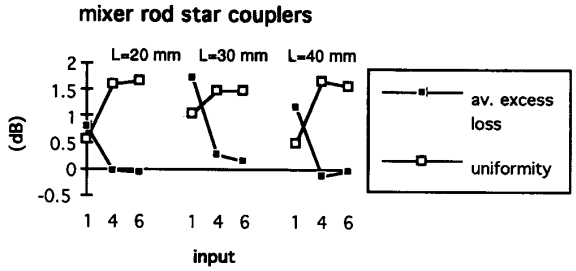

Fig. 13. Average excess loss and uniformity (standard deviation) of the outputs for inputs 1, 4, and 6 of the mixer rod star couplers.

The total loss in an interconnection path (one input to one output) consists of several parts:

$$\text{total loss} = \text{straight guide loss} + \text{splitting loss} + \text{excess loss}. \quad (8)$$

The straight guide loss includes absorption and scattering loss and is 0.35 dB/cm. The splitting loss to 1/8 of the power is fundamental and equals 9.03 dB. The excess loss depends on the geometry of the structure. It includes all losses due to the deviation of the structure from a straight guide, e.g., bending losses. In what follows we shall discuss the excess loss of the interconnection paths of the different star couplers.

A. Summary of Results

Table I shows the statistics over all measured interconnection paths (links) for each star coupler. The number of measured links is 24 for all structures (inputs 1, 4 and 6 to all outputs) except for the asymmetric tree structures, there we measured all 64 links. The standard deviation of the excess loss of the links is a measure for the uniformity of the output power of the devices. A small standard deviation or uniformity indicates that the splitter is uniform. This uniformity is also shown in the table.

Table I shows that the uniformity of the mixer rod devices is poor although the loss is low. The performance of this star does not improve for longer lengths L of the central mixing section. The tree structures have a better uniformity. The symmetric star, with extra long mixing lengths yields the best results. We will now discuss the measurements in more detail.

B. The Mixer Rod Star Coupler

Fig. 13 shows the average excess loss and uniformity over the 8 outputs for inputs 1, 4, and 6 of the mixer rod star couplers. The average excess loss depends on the input. The inner S-bends, that join the central mixing section close to its axis, have smaller losses due to their larger radius R. The uniformity of these structures is not so good, due to the different S-bend losses.

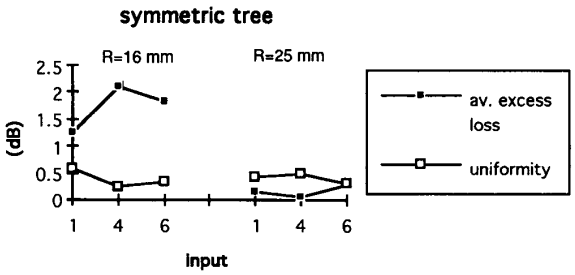

Fig. 14. Average excess loss and uniformity (standard deviation) of the outputs for inputs 1, 4, and 6 of the symmetric tree star couplers.

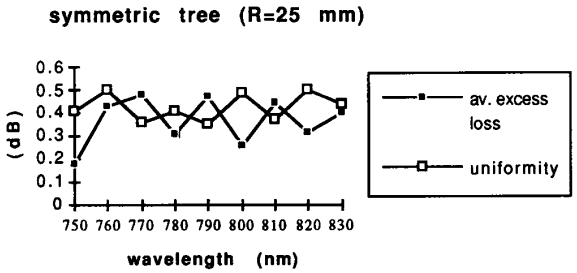

Fig. 15. Average excess loss and uniformity (standard deviation) of the outputs for input 1 of the symmetric tree star coupler (R = 25 mm) as a function of wavelength.

C. The Symmetric and Asymmetric Tree Star Couplers

The average excess loss and uniformity for 3 inputs of the symmetric tree star coupler is shown in Fig. 14. Low loss is measured for R = 25 mm. The uniformity is about 0.5 dB. Less than 0.5 dB is a good target for the uniformity of a star coupler, and we are near this target.

A collimated beam (NA = 0.05) from a tuneable Ti–Sa laser was coupled into input 1 of the symmetric tree. For different wavelengths, different modal distributions are excited. Fig. 15 shows the average excess loss and uniformity for all outputs versus wavelength. The uniformity is again about 0.5 dB and the loss corresponds with the values of Fig. 14. This measurement indicates also that the performance of this coupler does not depend much on the NA of the input beam.

The average excess loss and uniformity for all 8 inputs of the asymmetric tree star coupler is shown in Figs. 16 and 17. The uniformity is about 1 dB in both cases. The loss is below 1.5 dB for R = 25 mm.

D. Variations Due to Different Coupling Conditions

We measured variations due to different coupling conditions for the tree star couplers. The spot of the point source was moved to 9 different locations on the input facet. Fig. 18 shows the average excess loss and uniformity for (statistics over the 9 input locations) for all outputs and one input. The uniformity is about 0.5 dB for the symmetric tree (excitation

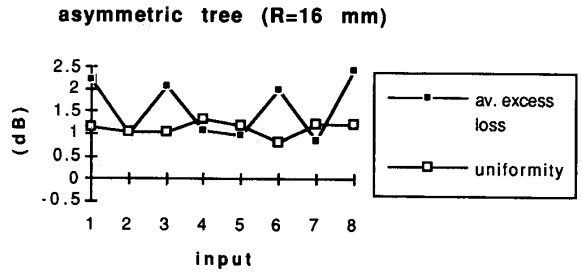

Fig. 16. Average excess loss and uniformity (standard deviation) of the outputs for all inputs of the asymmetric tree star coupler ($R = 16$ mm).

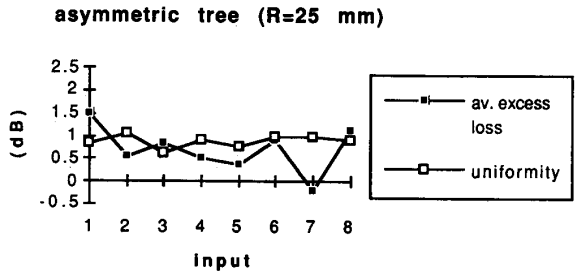

Fig. 17. Average excess loss and uniformity (standard deviation) of the outputs for all inputs of the asymmetric tree star coupler ($R = 25$ mm).

in input 1) and is only slightly larger for the asymmetric tree (excitation in inputs 1 and 4). Different coupling conditions excite different sets of modes. The value 0.5 dB is a measure for the fluctuations due to modal noise.

V. Discussion

Table I and Fig. 13 show that the measured performances of the mixer rod type do not depend on the length L of the mixing section. There is no trend that loss or uniformity improves for larger L. On the contrary, the performance is best for the shortest L. We conclude that the mixing is already optimal for $L = 2$ cm, as was predicted with the ray-tracing tool. The bad uniformity is probably due to the different losses of the S-bends, leading to different output power if the splitting was uniform.

The uniformity of the symmetric tree (see Table I and Fig. 14) is only slightly improved if R is changed from 16 to 25 mm. This again indicates that the mixing lengths are sufficiently long. The losses depend on R, with very low loss for $R = 25$ mm. Fig. 14 shows that there is no dependence of the loss and uniformity on the input, as was expected from the symmetry.

The symmetric tree has a uniformity that is twice as good as the uniformity of the asymmetric tree. This indicates that mixing lengths in the asymmetric tree have been chosen too short. Due to the asymmetry, the average excess loss depends on the input (see Figs. 16 and 17).

In the designs of the symmetric and the asymmetric tree, the same radius R has been used for all bent sections. However, we found that the loss of a circular bend is a function of w/R [7]. The same dependence on w/R is expected for S-bends.

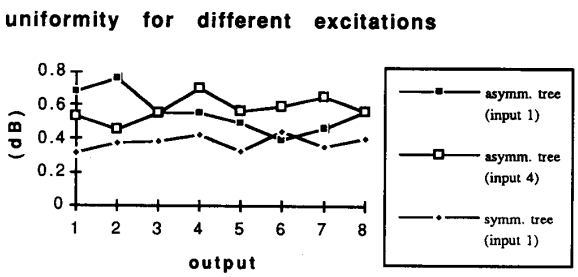

Fig. 18. Uniformity of the tree star couplers for different excitations with a point source.

Thus, if the S-bends in the tree-like designs have the same value for w/R, they will have the same loss. The losses will be distributed equally over all S-bends. For future designs we propose to take the same w/R for all S-bends.

VI. Conclusion

We designed 3 different types of 8 × 8 star couplers for various parameters, resulting in 7 designs. Two of the three types are based on trees of Y-branches, the third one on combining the 8 guides with S-bends to a central mixing section. In each of the designs the length of the waveguide sections in between the junctions was chosen such that the ray distribution was uniform.

Experimental results at 1.047 μm show low loss for all structures. The excess loss of the structures is mainly determined by the radius R of the bent sections. The uniformity of power at the output waveguides is best for the symmetric tree structure and is about 0.5 dB. Measurements with a tuneable Ti–Sa laser show that the loss and uniformity is independent of the wavelength in the range 750–830 nm. Furthermore, the loss and uniformity were found to be insensitive of changes in the coupling conditions of the focused laser beam onto input guides. This confirms again that the central mixing sections of the star couplers were well designed.

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