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# A High-Power SLED II Pulse Compression System*

N. M. Kroll,‡ Z. D. Farkas, T. L. Lavine, A. Menegat, C. Nantista,◊ R. D. Ruth, and P. B. Wilson

*Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309*

## INTRODUCTION

The enhancement of peak power by means of RF pulse compression has found important application for driving high energy electron linacs, the SLAC linac in particular. The SLAC Energy Doubler [1] (SLED), however, yields a pulse shape in the form of a decaying exponential which limits the applicability of the method. Two methods of improving this situation have been suggested: binary pulse compression [2] (BPC), in which the pulse is compressed by successive factors of two, and SLED II [3,4] in which the pair of resonant cavities of SLED are replaced by long resonant delay lines (typically waveguides). Intermediate schemes in which the cavity pair is replaced by sequences of coupled cavities (which may be thought of as forming slow wave structure delay lines) have also been considered [5,6]. In this paper we describe our efforts towards the design and construction of high-power SLED II systems, which are intended to provide drivers for various advanced accelerator test facilities and potentially for the Next Linear Collider itself. The design path we have chosen requires the development of a number of microwave components in overmoded waveguide, and the bulk of this paper will be devoted to reporting our progress.

Success achieved with the BPC, which is currently acting as driver for testing experimental accelerator sections, has demonstrated the suitability of overmoded circular waveguide operating in the $TE_{01}$ mode for use as delay lines. A low-power version of SLED II has been constructed which makes use of the same waveguide. Experiments carried out with this low-power version have confirmed the high-quality output wave form predicted by the theory [7]. Accordingly it has been decided to employ such waveguides in the SLED II system as well. This decision has driven the rest of the design. A schematic drawing of the proposed layout is shown in Figure 1. The system is being designed for high vacuum. The first realization (Prototype 1, hence P1) will make use of the same waveguide as that used for the BPC (WC281) with an inner diameter of 2.81 inches. The second (P2) will use a waveguide with a diameter of 4.75 inches (WC475) to reduce waveguide loss and hence enhance efficiency.

The same circular waveguide mode will be used in all SLED II components. The components required can be seen by reference fo Figure 1. A mode converter is needed to convert the rectangular $TE_{10}$ mode from the klystron to the circular $TE_{01}$ mode. This feeds into the 3-dB coupler, which consists of two circular waveguides coupled by a slot. The configuration requires the two waveguides to be very close together. Consequently, two S-bends, referred to as offsets, are needed to connect the coupler to the delay lines. This connection takes place through circular coupling irises whose properties are determined by the chosen pulse compression factor. To limit the length of the coupler and to reduce difficulties associated with the generation of other waveguide modes the waveguide diameter employed for these elements is 1.75 inches. Tapers are provided for transition between different waveguide diameters. Moveable end plates are provided in the delay lines for resonant tuning. A 90 degree bend connects the output port of the 3-dB coupler to the power transport line.

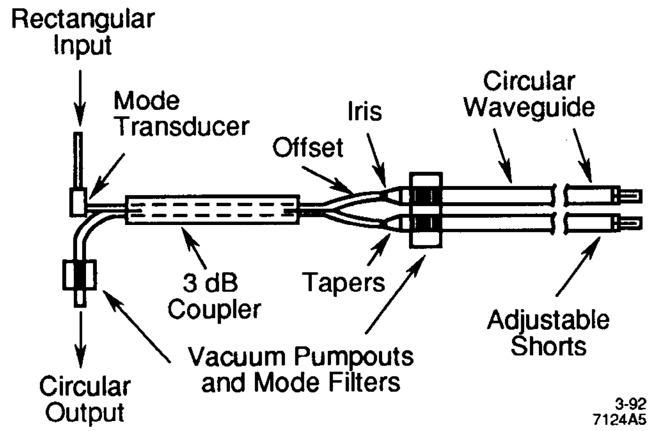


**Figure 1.** Schematic layout of a high-power SLED II system.

## STATUS OF THE COMPONENTS

### 1. *The 3-dB Coupler*

This is the most novel of the components, in that we are unaware of any other circular $TE_{01}$ mode 3-dB coupler of a suitable configuration. The heart of the device is two parallel circular waveguides connected by a slot of smoothly tapered width. The cross section can be thought of as that of a single waveguide. The design is based upon the behavior of the cutoff frequencies of the appropriate pair of modes as a function of the slot parameters. We refer here to the mode pair which, in the limit of zero slot width, are symmetric and antisymmetric combinations of the $TE_{01}$ modes in the two waveguides. The mode splitting determines the rate at which power transfers from one guide to the other (analogous to the coupled pendulum problem). Assuming power enters the upper waveguide on the left, the wave propagating to the right in the upper guide generates a wave propagating to the right in the lower guide. At the right end of the slot, power is reduced in the upper guide

* Work supported by Department of Energy contracts DE–AC03–76SF00515 and AS03–89–ER40527.
‡ Also Department of Physics, UCSD, La Jolla, CA.
◊ Visitor from Department of Physics, UCLA, Los Angeles, CA.

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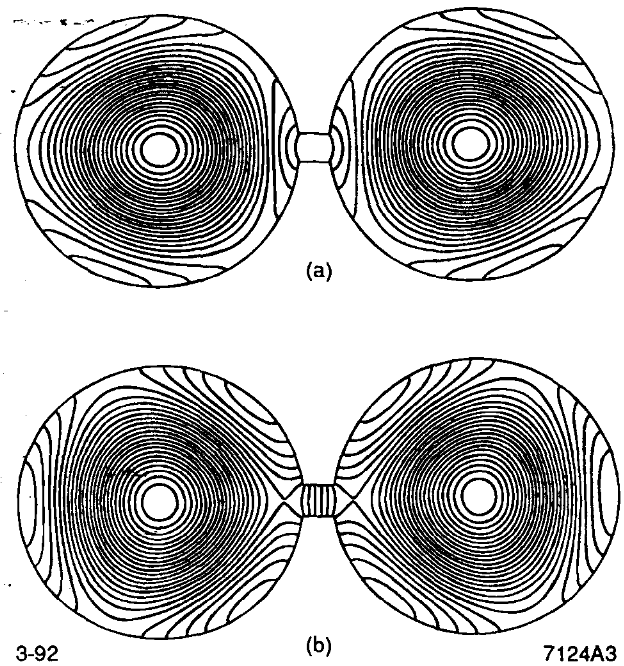


Figure 2. SUPERFISH plots of the electric field lines in the symmetric (a) and antisymmetric (b) $TE_{01}$ modes. Slot-induced distortion of the fields is apparent.

by a factor of $\cos^2\phi$, and $\sin^2\phi$ times the incident power appears in the lower guide, where, to a good approximation

$$\phi = \frac{k_c}{2\sqrt{k^2 - k_c^2}} \int_0^L (k_{ca} - k_{cs})\, dz \ .$$

Here $k_{ca}$ and $k_{cs}$ are the cutoff wavenumbers of the antisymmetric and symmetric modes respectively, $k_c$ that of the unperturbed $TE_{01}$ mode, and $k$, the free space wavenumber.

In order to compute the dependence of the mode splitting on the slot parameters we used a semianalytic method based upon field matching at the junctions of the circular waveguides with the connecting slot. These calculations provided us with a global picture of the dependence of the mode splitting on the slot parameters. After fixing the main features of the design, SUPERFISH calculations were performed as a check and also to provide information on the field distribution. Figure 2 provides an example of the field distribution of the symmetric and antisymmetric $TE_{01}$ modes and shows the distortion of the $TE_{01}$ mode pattern caused by the connecting slot. As a further check, a short section of the waveguide was constructed and fitted with shorting plates, and the resonant frequencies of the resultant cavity were compared to those determined by the calculations.

The slot was designed to yield $\phi = \pi/4$ at 11.424 GHz. Because the coefficient of the integral above is frequency dependent, $\phi > \pi/4$ below the design frequency and $< \pi/4$ above the design frequency. Figure 3 illustrates the performance of the coupler as observed

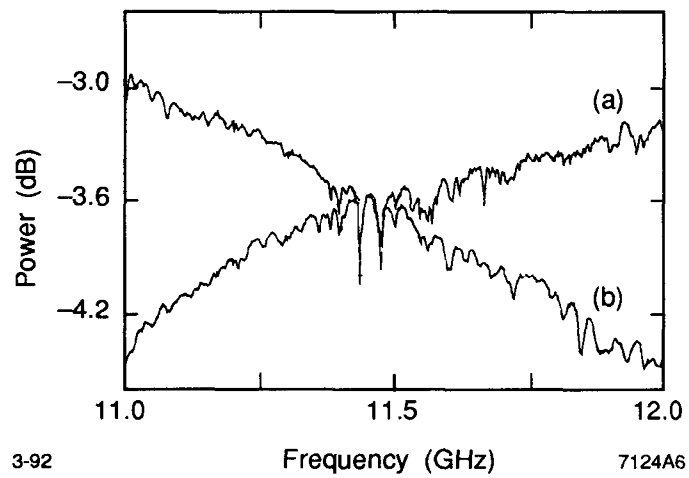


Figure 3. Observed power transfer in the 3-dB coupler plotted as a function of frequency. Power enters one of the waveguides and emerges partially from the output end of the same waveguide (curve a) and partially from the waveguide to which it is transferred (curve b). Power passes through two offsets.

with a Hewlett-Packard network analyzer, demonstrating near equal power division at the design frequency and the expected variation of power division with frequency. Pulse transmission tests of the coupler and two offsets showed that the bandwidth is sufficient to process short rise time pulses without noticeable degradation. Approximately 0.4 dB of the 0.6 dB loss shown in Figure 3 is in the chain of components between the network analyzer calibration ports and the combination of offsets and 3-dB coupler. This chain includes two WR90 waveguide bends, two mode converters, and two mode filters. An alternate measure of the loss, particularly relevant to the way the coupler is used in SLED II, is obtained by measuring the transmission from the input to an adjacent port when the ports on the opposite end are shorted. Such a measurement doesn't depend on the quality of available matched loads and does not involve trying to measure a small increment to a 3 dB loss. Furthermore, it involves two passes through the coupler and a pass through two offsets, which should make the coupler loss more apparent. The loss observed in this situation was estimated to be less than 0.1 dB, the spikiness of the transmission making it difficult to be more precise. The transmission through two offsets without the coupler was also measured and was essentially indistinguishable from the case above. More measurements and better technique are required to obtain more consistent results, but we feel confident that the loss of the coupler plus offsets is no more than 0.2 dB and is probably substantially less. The fourth-port isolation observed when the output ports were terminated in approximately matched loads was 35 dB.

The 3-dB coupler described above was machined in two halves on a milling machine, and the two halves were then bolted together. Consequently it is not suited for direct incorporation into a vacuum system. While it would be possible to reassemble it in vacuum tight brazed form, we have instead constructed a vacuum chamber in which it will be enclosed.

### 2. *The Offsets (S-Bends)*

The S-bends consist of two circular arcs connected by a straight section. In designing an S-bend, one can take advantage of the fact that the $TE_{01}$ to $TM_{11}$ conversion in the first arc is to first approximation undone by the second. Conversion to other propagating modes is oscillatory. Arc lengths and straight section length are chosen to minimize conversion at the end of the bend, and the theoretically computed conversion loss is less than 0.005 dB. Resistive losses would be expected to be larger, perhaps as much as 0.03 dB for our larger offsets. The bends used in the measurements reported above were rather crudely made. They introduce a difficult to measure but noticeable loss (<0.1 dB each), but we would hope that their loss could be made to approach theoretically expected values. For use in the prototype system, new offsets which provide for increased separation have been designed and constructed. These are more carefully made but have not yet been fully tested. Preliminary observations suggest that they are comparable to the original ones and will be suitable if not optimal for inclusion in P1.

### 3. *Mode Converters*

The experimental observations reported above were made using Marié type mode converters supplied by Antennas for Communication Corporation. For carrying out measurements we have found it to be desirable to follow each of them by a six-inch mode filter which radiates out residual conversion to undesired modes. While the mode filters appear to have a negligible effect on the $TE_{01}$ mode, they do introduce an extra 0.1 dB loss in the mode converter output which we attribute to such modes. Measurement problems which we attributed to the presence of undesired modes were greatly ameliorated by introduction of the mode filters. The BPC employs mode converters supplied by General Atomics, but these were not available for these measurements. We have no evidence that they would be any better. The combination of two mode converters plus two filters produces an overall loss of 0.35 dB and is long and bulky. We are currently working on adapting an Alpha Corporation design (at KU band) for use at our X-band frequency. It is much more compact than those mentioned above. Our preliminary work leads us to believe that, with this design, it may be possible to achieve better mode purity and lower loss. It is, however, inherently more narrow band, and its power handling capacity must be confirmed.

### 4. *The 90-Degree Bend*

Figure 1 shows a 90-degree bend at the output port of SLED II. This is one of a few bends needed in the power transport system. Because of the degeneracy between the $TE_{01}$ and $TM_{11}$ modes of circular waveguide, design of such a bend is nontrivial. We have ordered a pair of bends from General Atomics to be made with circular corrugated waveguide of 1.75 inch diameter. We are also working on a design of our own which may be simpler to make. Which of the two will be better RF-wise can only be determined after they are in hand.

### 5. *Delay Line Components*

For Prototype 1, each delay line requires an iris in WC175 guide, a taper to the WC281 delay lines, the delay lines themselves, and a vacuum adjustable moving short. To minimize conversion to other modes it is important to preserve perpendicularity in the short as it is moved. All of these parts are ready for assembly. Pumping manifolds are also required, and possible locations are indicated in Figure 1. The pumping manifolds will be designed so as to act as mode filters as well.

## FUTURE PLANS

The Prototype 1 configuration, as described in the introduction, will be assembled in the very near future. The output pulse length will be about 100 ns, with a power gain up to 4.8 for an input pulse length of 800 ns. A nearby X-band klystron, also being developed as part of the Next Linear Collider R&D program, should provide sufficient power to drive the P1 configuration to a power output level on the order of 150 MW.

The main purpose of the P1 tests will be to verify the high-power capability of the 3-dB coupler. The output power will therefore be delivered to a high-power load attached to the output port of the coupler. The P2 configuration, on the other hand, will be able to deliver useful power to prototype accelerating structures located in a shielded test bunker about 12 m from the coupler. Because the losses in a WR90 waveguide run of this length would be intolerable, part of the P2 configuration will be an overmoded circular waveguide transport system using the 90 degree bends under development. This pulse compression system, operating at an output pulse length of 150 ns, will be a final prototype for the NLC Test Accelerator facility being proposed at SLAC. It is hoped that the P2 system will be ready for high-power tests in Autumn 1992.

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