Optimized Irregular Structures for Spatial- and Temporal-Field Transformation

Tanveer ul Haq, *Member, IEEE,* Kevin J. Webb, *Senior Member, IEEE,* and Neal C. Gallagher, *Fellow, IEEE*

(Invited Paper)

***Abstract*—In a bounded region such as a waveguide, a mode is an eigensolution of the electromagnetic-wave equation with particular boundary conditions imposed. Conversion from one mode to another through a mode converter could be accomplished by using a scatterer located within the waveguide. Generalizing to an arbitrary domain, either within a waveguide or in unbounded media, a field transformer converts one spatial field to another as a function of frequency. With this interpretation, a hologram is a field transformer, as is a mirror, filter, grating and spatial switch. Mode-control elements usually employ periodic structures, e.g., as is the case in ripple-wall waveguide-mode converters and photonic bandgap structures. A special case of this mode conversion is filtering (amplitude and phase control) with the same input and output mode. We have developed a new kind of field transformer which uses aperiodic structures. Specific designs are arrived at through numerical optimization of a cost function representing the mode transformation. Rather than effecting field transformations using a series of small geometry perturbations, our concept forcefully changes the field using an optimized structure. The optimization process allows consideration of a number of electrical and mechanical issues, such as efficiency, bandwidth, size, and amenability to manufacture. Of particular importance is the large parameter space afforded by the propagating and evanescent modes. We anticipate many opportunities in this area, facilitated by the continual reduction in cost of computing power. We present designs for microwave mode converters using our optimized irregular structure concept and compare them with those achieved using a periodic coupled-mode concept. These designs show dramatic improvements in performance and physical size, while incorporating a dimensional constraint and sensitivity analysis that provides for ease in fabrication. A combined mode converter and transition between differing waveguides is illustrated by a device we built and tested at X-band. A power combiner or splitter is posed as a mode-conversion problem, as is the microwave phase shifter. Implementations of dielectric filters and frequency-dependent spatial switches are also suggested using optimized scattering elements.**

***Index Terms*—Diffractive elements, microwave phase shifters, mode control, mode converter, power combiner/splitter, waveguide transitions, wavelength division multiplexer.**

Manuscript received July 28, 1998.

T. ul Haq is with Lucent Technologies, Whippany, NJ 07981 USA (e-mail: haq@lucent.com).

K. J. Webb is with the School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN 47907 USA (e-mail: webb@ecn.purdue.edu).

N. C. Gallagher is with the Department of Electrical and Computer Engineering, University of Delaware, Newark, DE 19716 USA (e-mail: gallaghe@eecis.udel.edu).

Publisher Item Identifier S 0018-9480(98)08330-6.

I. Introduction

WE DEFINE a mode converter as a passive structure, which converts a mode or set of modes at the input to a single or set of modes at the output, where each mode is an eigenfunction of the Helmholtz wave equation in a finite domain. To encompass the unbounded media situation, we generalize "mode converter" to a field transformation device to emphasize that the concept involves changing the spatial and temporal (frequency-dependent) character of an excitation to a desired output response.

Mode-control and conversion devices find wide application in microwave and optical engineering. Microwave applications include waveguide mode converters, multimode feeds for radar systems, waveguide transitions and tapers, phase shifters, microwave heating systems, waveguide mode launchers, waveguide couplers, and mode filters. Examples of optical mode converters or field transformers are waveguide couplers, spatial filters, holographic elements, spectral filters, and photonic bandgap structures. The goal of all of these structures is to filter, preserving the spatial field variation, or to change from an input spatial field to another at the output. In the waveguide case, there are many possible operations that one may wish to perform on a mode or set of modes, such as induce radiation, couple between waveguides, transform to a single mode or a set of modes at the output, or impose a variable phase shift.

The concept of using periodic structures to realize field transformation functions stems from lumped-element filter synthesis techniques, weakly coupled harmonic oscillation or coupled-mode theory, and an understanding that has evolved based upon the scattering from naturally occurring periodic crystal structures. For adequate performance in microwave and optical applications, mode-control structures based on periodic notions are inevitably long, relative to the wavelength. This is a major concern in microwave applications, where, e.g., a mode-converter's length is dictated by the beat wavelength for the two modes involved, which could be very long indeed. In addition, while providing a convenient analytic design platform, use of periodicity precludes many, possibly desirable, solutions.

We have introduced the concept of mode control through irregular optimized elements [1]. In this paper, we present a family of aperiodic and irregular structures designed as mode-control devices with significant advantage over periodic structures in terms of size, performance, and ease of fabrication. We generalize the scattering optimization method

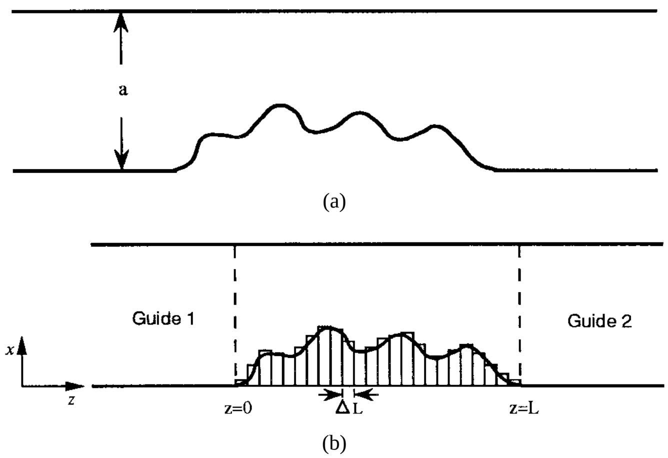

Fig. 1. (a) Continuous scatter in a metal-walled waveguide. (b) Staircase discretization of the scatterer in (a).

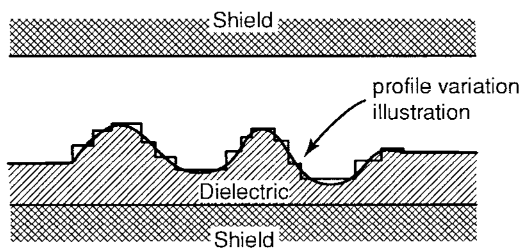

Fig. 2. Shielded dielectric waveguide to preclude radiation. Simpler analysis results and fabrication could be achieved through micromachining.

(SOM) for the design of such devices [1]. The domain of all possible shapes and material compositions can potentially be explored, resulting in devices which are not intuitive, which may have irregular shapes, but which can perform better than periodic structures in many cases. For instance, the use of a metal-walled waveguide variation to induce scattering, shown in Fig. 1(a) and (b), and the variation of the surface profile of a shielded dielectric waveguide in Fig. 2 are examples of irregular scattering geometries that could be optimized to achieve a particular mode transformation. We also review our achievements to date and suggest several mode control and transformation applications.

Section II of this paper presents a generalized formulation of the SOM by which not only the staircase surfaces, but other families of structures and material compositions can be explored for the design of optimum mode-control devices. Sections III and IV present comparisons of microwave circular waveguide mode converters designed using the traditional periodic approach and also using our optimized irregular solution, along with a review of some of our earlier results, including a transition and mode converter fabricated at X-band [2]–[4]. Sections V and VI outline concepts for microwave waveguide power splitters and combiners and also phase shifters based on the optimized mode-control concept. Optimized microwave or optical dielectric stack filters are outlined in Section VII. Finally, in Section VIII, we suggest a frequency/wavelength-dependent ("optical") switch realized using optimized diffractive elements for applications such as fiber wavelength division multiplexing (WDM).

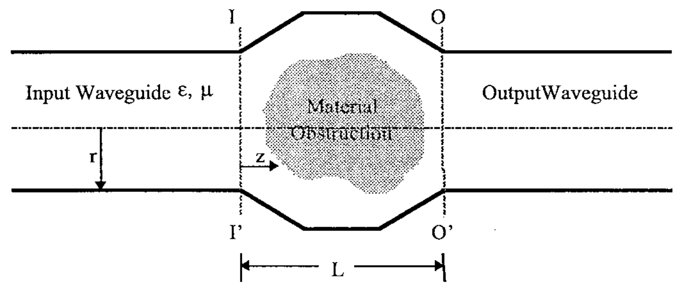

Fig. 3. Obstruction placed in the path of an electromagnetic wave scatters energy into various waveguide modes.

II. Nonlinear Optimization Solutions—The SOM

Consider electromagnetic mode control in a waveguide. In general, the following three quantities describe the waveguide:

1) profile $p(\mathbf{r})$;
2) permittivity $\epsilon(\mathbf{r})$;
3) permeability $\mu(\mathbf{r})$

where $\mathbf{r}$ is the position vector. Each of these quantities could be represented as a superposition of complete domain or subdomain basis functions, such as pulse, rooftop, Chebyshev, or sinusoidal functions, implying that the mode-control element is then defined by the weights for these basis functions. The optimization problem is then to maximize a desired quantity, such as the power out in a particular mode, which can be couched in terms of a cost function which is to be minimized. The forward problem requires a numerical electromagnetic solution with sufficient accuracy to capture the influence of the waveguide variations. For instance, in a conducting wall waveguide with a local region eigenfunction expansion or mode-matching solution, an adequate number of evanescent modes need to be well represented to have a convergent solution. Clearly, the parameter space could be quite large. We have investigated approaches to reduce the number of free variables in each optimization step, e.g., waveguide problems (circular and parallel-plate waveguide, thus far), and arrived at the SOM [2], [3], [5]. The technique is not sophisticated, but it has served the purpose of achieving a series of designs that were computationally tractable and which permitted comparisons with regard to performance and amenability to fabrication.

Consider a generalized formulation of the SOM [6], [7] for the design of mode-control and conversion devices. The domain of all possible shapes and materials is explored to find a scattering obstruction which, when placed in the path of the incoming wave, will convert power from a set of modes (one or more) to a single mode at the output. This approach is completely general and neither restricts itself to a specific type of pattern variation, nor to a particular nonlinear optimization algorithm. Structures obtained with this method have aperiodic variations and can be very irregular in shape.

The idea behind our design technique is to place an obstruction in the path of the incoming electromagnetic field, as shown in Fig. 3. The shape, size, and material of the obstruction is totally arbitrary. When the incoming field interacts with the obstruction, it scatters into various modes of propagation. A procedure is then adopted to optimize the shape, size, and

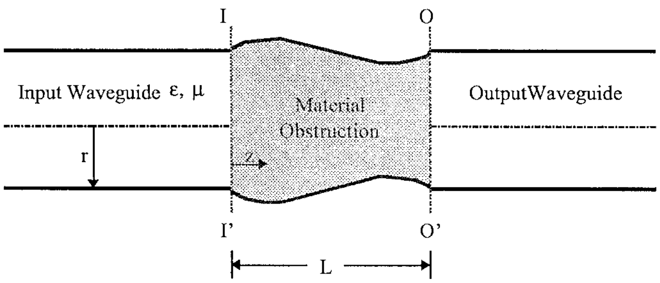

Fig. 4. Longitudinally varying waveguide scatterer.

material of the obstruction so as to maximize the power scattered into the required mode (or set of modes) at the output. The size and shape of the input and output waveguides is arbitrary, and the obstruction can protrude outside the dimension of either waveguide.

Consider the case of a completely filled circular waveguide scatterer where the conducting wall boundary varies as a function of z, as in Fig. 4. This concentric waveguide is azimuthally symmetric, i.e., it has no ϕ-variation, but has a z-varying ϵ, μ, and conducting wall boundary. Such a structure can transform only the radial mode index of the incoming mode. Specifically, the following conversions are possible: TE_{mn} to TE_{mp}, TE_{mn} to TM_{mp}, TM_{mn}, to TE_{mp}, and TM_{mn} to TM_{mp}.

The z-variations in the shape and material properties of the obstruction can be represented by using suitable basis functions. The waveguide shape is defined by a change $\Delta r(z)$ from an input waveguide radius r by

$$\Delta r(z) = \sum_{q=1}^{Q_r} a_{rq} f_{rq}(z) \tag{1}$$

where Q_r basis functions with weight a_{rq} are used in an incomplete set and, e.g., $f_{rq}(z) = U(z-z_q)$, $J_q(z)$, or $\sin(qz)$, with $U(z)$ the unit step function and $J_q(z)$ the Bessel function of the first kind of integer order q. The obstruction spans the physical space $O < z < L$. Given that r is the radius of the (reference) input waveguide, then $\Delta r(z)|_{\min} > -r$ and $\Delta r(z)|_{\max}$ is dictated by practical constraints.

Similarly, for this z-varying waveguide, the electrical properties (the dielectric constant, ϵ) can be expressed in terms of a basis set as

$$\Delta\epsilon(z) = \sum_{q=1}^{Q_\epsilon} a_{\epsilon q} f_{\epsilon q}(z) \tag{2}$$

where $a_{\epsilon q}$ are the permittivity weights, and the basis functions are not necessarily those of (1). If ϵ is the dielectric constant of the material in the input waveguide, then $\Delta\epsilon(z)$ is the change in ϵ as a function of z, and the total z-support is again L.

Likewise, the magnetic properties (magnetic permeability μ) can be expressed as

$$\Delta\mu(z) = \sum_{q=1}^{Q_\mu} a_{\mu q} f_{\mu q}(z) \tag{3}$$

where, in this case, $a_{\mu q}$ are the permeability weights and $\Delta\mu(z)$ is the change in μ as a function of z.

Note that for $U(z - z_q)$ with $z_q - z_{q+1} \ll \lambda$, the resulting staircase structure can fit arbitrarily close to a continuous surface as the step length approaches zero, as illustrated in Fig. 1(b). The functional representation of $\Delta r(z)$, $\Delta\epsilon(z)$, and $\Delta\mu(z)$ are arbitrary and each can differ in spatial dependency. This variation is, of course, limited in reality by the physical materials available and achievable dimensions.

The power scattered by this structure at the output plane in a particular mode N, P_N is then a function of all the variables, i.e.,

$$P_N = P_N(a_{rq}, a_{\epsilon q}, a_{\mu q};\, f_{rq}, f_{\epsilon q}, f_{\mu q};\, Q_r, Q_\epsilon, Q_\mu;\, L). \tag{4}$$

In the SOM, P_N is optimized as a function of the variables in (4) to maximize the power converted into the required mode. Optimized values of the variables then represent the required design of the mode-control device.

Even with a modest number of degrees of freedom, the optimization problem is very demanding because a forward numerical solution of Maxwell's equations is required at each iteration. For example, to optimize, say, 50 variables simultaneously is a difficult problem. Most global optimization techniques work best when the number of variables is limited to several (smaller than the number we have found is necessary for satisfactory mode conversion). Therefore, in order to facilitate the mode-converter design, a hierarchical sectional optimization procedure has been formulated. We start with a very coarse estimate for the features of the mode-control device. This is done by just a few terms in the basis function representation of the shape/material and a small length L, to keep the initial number of variables small. These variables are optimized to obtain a coarse estimate of the final structure. More terms are then added in the series and L is also increased, thus increasing the number of variables and also refining the representation of the mode transducing obstruction. Optimization is again carried out and the procedure is repeated until a suitable mode converter is identified. Due to a small number of variables in earlier stages of optimization, a lot of computation time is saved. However, in the later stages, the number of variables can become very large. In order to do a global optimization of all these variables, a sectional optimization procedure is implemented. Consider that a global optimization technique is being used, which converges best when the number of variables is restricted to two, whereas the number of variables to be optimized is 50. The 50 variables are optimized two at a time, starting with the first two. While optimizing a set of two, the other variables are kept constant. When all the 50 variables have been optimized once, the iterative sequence is repeated again. The sectional optimization sequence is continued until convergence is achieved for all the 50 variables.

It may be observed that truncation of the series in (1)–(3) to a small number of terms, at the start of hierarchical optimization, is akin to restricting the search domain of possible structures for mode conversion. If the desired solution is not obtained in this restricted domain, the number of terms in the series and/or length L is increased and a larger domain of possible structures is now searched. This procedure is continued until an appropriate structure is identified. Thus, the SOM does not make any presumptions about the final shape of the device.

The hierarchical procedure defined above does not result in unique solutions for mode-conversion structures because the number of free variables is much greater than the cost function constraints. Depending upon the constraints and initial guess for optimization and the type and number of basis functions, various solutions can be obtained for the same problem as a consequence of the underconstrained system. This gives a suite of possible designs that can be evaluated for desirable features. A step-by-step implementation of a specific design is given elsewhere [7], [8].

III. Aperiodic Microwave Mode Converters for High-Power Applications

In this section, various circular waveguide mode converters are presented which utilize irregular structures for mode conversion and were designed using the SOM. In this particular application of the SOM, only the waveguide shape is changed by varying the radial dimension using a step–function basis set in (1), resulting in a staircase pattern for the shape of the mode converter.

Due to the development of high-power high-frequency gyrotrons, there has been considerable interest in mode converters to transform the higher order TE_{0n} modes at the gyrotron output to the lower order, lower loss TE_{01} mode. The TE_{01} mode is then transformed into the TE_{11} mode or better yet, the HE_{11} mode, for plasma heating. Various TE_{0n}-to-TE_{01} mode converters have been designed for these applications using coupled-mode theory. Frequencies of considerable interest have been 28, 60, and 140 GHz [9]–[16].

Periodic gratings have been used frequently to design mode-control devices for waveguides [9], [10], [17]. These mode converters can be formed by periodically varying the transverse dimensions of the waveguide to produce a perturbed rippled-wall structure, a diffraction grating. Apart from slight modifications in the perturbation profile, these designs are primarily based on the technique developed by Kovalev *et al.* [12], utilizing coupled-mode theory [9]–[20]. Good conversion efficiencies have been reported for these gratings, but their lengths remain large compared to the waveguide transverse dimension. Despite efforts to optimize the size of the rippled-wall mode converter, the overall length of conversion is limited by the grating period

$$\delta = 2\pi/|\beta_m - \beta_n| \tag{5}$$

where β_m and β_n are the propagation constants for the input and output modes. The problem with this perturbation design method is that it restricts the design space to periodic structures. An infinitely large domain of aperiodic surfaces is ignored and, therefore, the options for improving the performance and reducing the length of mode converters are limited.

A mode-matching method is used to implement the forward solution of the waveguide discontinuity problem [1], [21]–[26]. The mode-matching method allows for accurate calculation of the power in the required output mode if a sufficient number of evanescent modes are included in the calculations. The power in the required output mode is then optimized as a function of the step radii in the staircase pattern by using equal lengths for each uniform section. There are certain design criteria in the SOM that can affect the final shape and properties of the designed mode converter, and these can be altered to control the shape, size, and performance of the aperiodic mode converters [4], [8]. They include the initial guess, where different initial guesses can result in different shapes because of the nonuniqueness of the solutions: $r_{\max}$, the maximum allowable protrusion outside the waveguide walls, $\Delta L_{\min}$, the minimum thickness for each uniform section in the staircase pattern, and Δr, the increment value for the variables (radii) in the optimization procedure. The values of $r_{\max}$ and $\Delta L_{\min}$ affect the size of the mode converter. A larger $r_{\max}$ and smaller $\Delta L_{\min}$ result in shorter converters. The minimum increment value for the radii during optimization should be established based upon the accuracy of the fabrication process.

The metric we use for success is the efficiency of mode conversion, which is defined as

$$\eta = \frac{P_N}{P_{\mathrm{in}}}. \tag{6}$$

Note that in computing η in (6), P_N is the transmitted output power in the desired mode and that losses in all reflected mode powers and all transmitted powers in other modes are included.

Irregular staircase designs for various mode converters are now presented and compared with previously reported rippled-wall designs. The numerical results for these mode converters and comparisons with the rippled-wall designs are provided in Table I. For each scattering optimization design, selected values for $r_{\max}$ and $\Delta L_{\min}$ are also provided. These results indicate that there is a family of irregular structures that can perform mode conversion with similar or better efficiency and have lengths much shorter than the corresponding rippled-wall devices.

One of the shortest mode converters designed using coupled-mode theory has been reported by Buckley *et al.* for a 60-GHz gyrotron [15]. In this case, the output of the gyrotron is composed of a TE_{02} mode and is coupled into a waveguide of diameter 6.35 cm. The waveguide is tapered down to a diameter of 2.779 cm (radius $r = 1.385$ cm) and the mode converter is designed for this smaller waveguide. The rippled-wall design reported has an efficiency of 97% and a length of 18 cm, which is equal to one ripple period δ. To design an aperiodic mode converter for this application, an initial guess of length 4.8 cm and a step length of 1.2 cm was assumed in the SOM [3]. The maximum-allowed radius for a protrusion was selected as $r_{\max} = 4$ cm and the minimum thickness of each uniform section is $\Delta L_{\min} = 1.5$ mm. The designed staircase mode converter is shown in Fig. 5. It has a length of 9 cm (improvement by a factor of two), an efficiency of 97.86%, and 1% bandwidth of 30 MHz. The 1% bandwidth is defined here as the bandwidth for 1% reduction in the conversion efficiency of the mode converter.

TABLE I

SUMMARY OF RESULTS FOR CIRCULAR WAVEGUIDE TE_{on} TO TE_{01} CONVERTERS. NOTE THAT THE BANDWIDTH GIVEN FOR THE PREVIOUS DESIGN OF A TE_{04}–TE_{01} CONVERTER IS FULL WIDTH HALF MAXIMUM (3 dB), DENOTED BY *, AND THAT ALL OTHER BANDWIDTHS ARE FOR THE 1% POINTS

Converter Type	Freq. (GHz)	Waveguide Radius (cm)	Previous Designs				Scattering Optimization Designs					Comparative Length L_p / L_s
			Ripple Period δ (cm)	Length L_p (cm)	Efficiency (%)	Bandwidth (MHz)	$\Delta L_{min} / \lambda$	r_{max} / r_0	Length L_s (cm)	Efficiency (%)	Bandwidth (MHz)	
$TE_{02} - TE_{01}$	60	1.385	18.0	18.0	97.6	3000	0.3	2.89	9.0	97.86	30	2
$TE_{02} - TE_{01}$	28	3.175	20.341	81.364	97.0	150	0.233	1.89	10.0	98.71	200	8.14
$TE_{06} - TE_{01}$	140	1.39	1.795	179.5	99.2	140	9.933	2.52	37.2	96.70	24	4.83
$TE_{04} - TE_{01}$	34.95	2.1	1.832	58.0	98.7	420*	0.583	2.38	16.0	98.71	36	3.63
							0.292	2.86	12.5	99.5	33	4.64

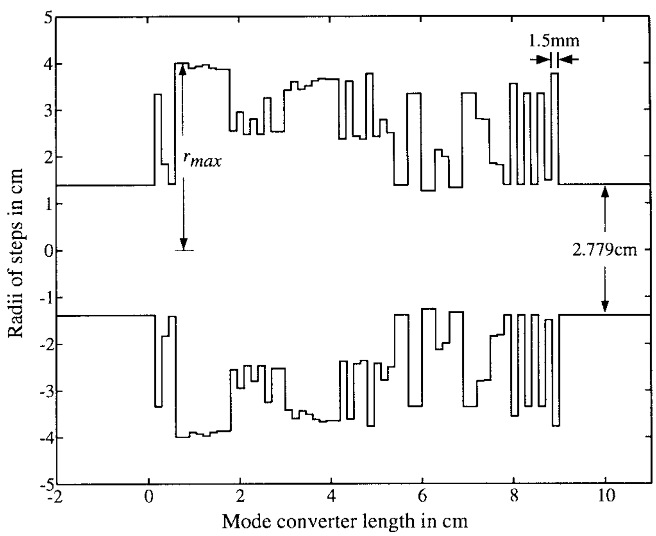

Fig. 5. Profile of a circular waveguide TE_{02}-to-TE_{01} mode converter at 60 GHz.

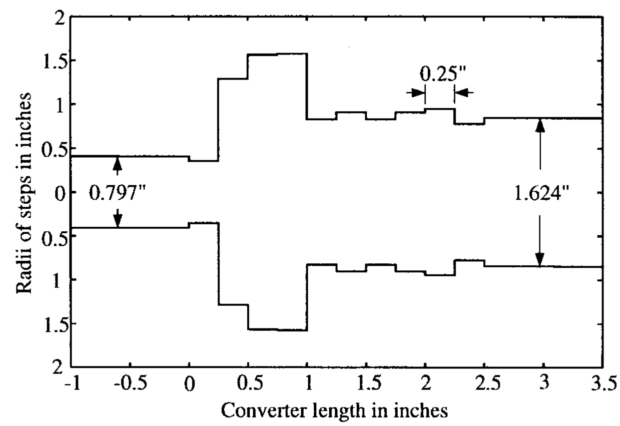

Fig. 6. Cross section of an aperiodic design for a TE_{11}–to-TM_{11} mode converter and transition between different-sized waveguides having a nominal operating frequency of 9.94 GHz.

Otsuka *et al.* have reported a TE_{02}-to-TE_{01} mode converter for a 28-GHz gyrotron output in a waveguide of diameter 6.35 cm [16]. Their mode converter has an efficiency of 97% and its length is 83.4 cm, which is equal to four ripple periods (4δ). The aperiodic mode converter designed for this application [2] has a length of 10 cm (improvement by a factor of eight) and it has an efficiency of 98.71%.

Another example is the 140-GHz TE_{06}-to-TE_{01} mode converter reported by Kumric *et al.* [13]. The aperiodic mode converter in this case resulted in about five times reduction in size with comparable efficiency [2].

In order to demonstrate the effect of $r_{\max}$ and $\Delta L_{\min}$ on the overall design of the mode converter, a TE_{04}-to-TE_{01} mode converter was designed for 34.95 GHz by using two different sets of values for $r_{\max}$ and $\Delta L_{\min}$ [4], [8]. By increasing $r_{\max}$ and reducing $\Delta L_{\min}$, the overall length of the mode converter was reduced. In Table I, the two mode-converter designs are compared with a previous design reported by Levine [10] for this application.

Bandwidth was not included as a parameter to be optimized in the design of the mode converters reported in Table I. If two designs had the same efficiency of conversion, then the one with larger bandwidth was selected. It can be seen from the data that, in general, the aperiodic mode converters are much shorter than the periodic structures and do not necessarily have either larger or smaller bandwidth.

The discrete and abrupt conducting wall step used in realizing the mode-converter examples may not be suitable for high-power applications because of increased electric-field magnitude in the vicinity of the steps. This difficulty can be circumvented by using smoother wall geometries and possibly dielectric liners. The coarse step really provided solutions with a relatively small variable set and simple basis functions.

IV. A SINGLE APERIODIC DEVICE FOR WAVEGUIDE TRANSITION AND MODE CONVERSION

Apart from the transformation of one mode to another, the irregular structures designed using the SOM allow for conversion of a set of modes into a single mode at the output. If this transformation is for modes at the same frequency, then the phase relationship between the incident modes must be known. Given this, aperiodic structures can be used for designing mode filters [3]. Another application of irregular surfaces is in the design of waveguide transitions [3]. In this section, a device is described that was designed to transform a TE_{11} mode in a smaller waveguide to a TM_{11} mode in a larger waveguide [2]. This device, therefore, acts both as a waveguide transition and mode transducer.

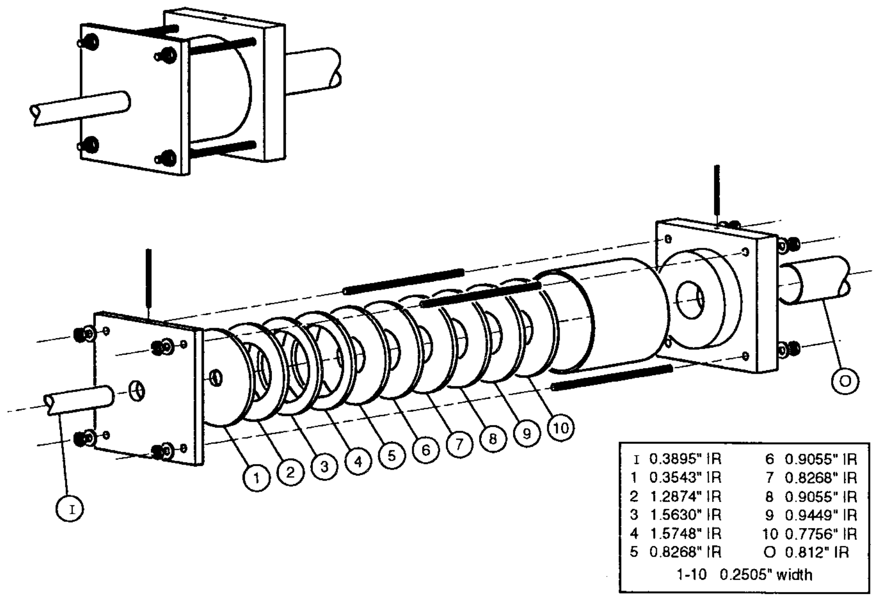

Fig. 7. Sectional view of the TE_{11}-to-TM_{11} mode converter (inner radius: IR).

The cross sections of the design is given in Fig. 6. The device was designed at a center frequency of 9.94 GHz. The input waveguide has a 0.3894-in radius, which ensures that this waveguide is single mode and only the lowest order TE_{11} mode propagates. The output waveguide has a radius of 0.812 in and it can propagate both the TE_{11} and TM_{11} modes. The profile of the mode converter designed for this application consists of a staircase model, as shown in Fig. 6. It has ten steps in the staircase with a width of 0.2505 in for each step. This design was selected out of many designs which were developed using the SOM with different initial guesses. Each design was evaluated based upon its conversion efficiency and its ability to tolerate fabrication errors. The design shown in Fig. 6 has a conversion efficiency of 99.5%.

To demonstrate the practical feasibility of irregular structures for waveguide mode control, this device was fabricated using a cost-effective method. Instead of using earlier techniques of preforming or molding for the fabrication of microwave mode converters, a new modular approach to the construction of waveguide mode converters was adopted. Standard copper/brass tubing were used as input and output waveguides and the discs for the uniform sections of the mode converter were machined out of a 0.25-in-thick sheets of aluminum. The discs and waveguide were appropriately secured and the device was assembled, as shown in Fig. 7. A coaxial SMA launcher with an extended center conductor was used to excite the TE_{11} mode in the input waveguide. The length of the waveguide was so selected that any evanescent modes excited at the launcher would be negligible at the input plane of the mode converter.

A far-field radiation pattern measurement method [2], [8], [27], [28] was implemented to characterize the mode converter. This method assumes that all the propagating modes in the waveguide are coupled into the free space and there are no reflections or cross coupling at the transmitting end of the waveguide. To achieve a low-loss transition to free space, a dual-mode horn antenna was fabricated to produce satisfactory coupling to free space [29]. The horn exit plane radius is 2.72 in, which is wide enough for a smooth coupling of TM_{11} and TE_{11} modes into free space. The measured far-field pattern of the horn indicated 98.1% of the power to be in the TM_{11} mode at the nominal center frequency. The measured results in Fig. 8 indicate a 1% bandwidth around the center frequency of 40 MHz. The measured conversion efficiency and bandwidth were found to be in close agreement with the theoretical values [2]. They were also qualitatively supported by a waveguide slotted line measurement.

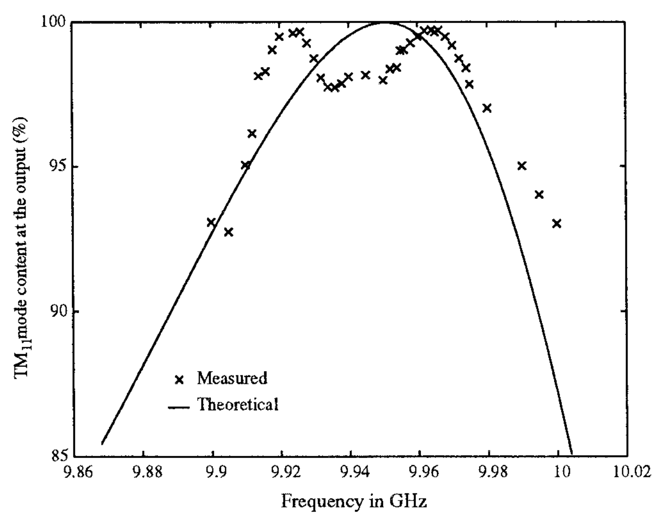

Fig. 8. Measured efficiency for the TE_{11}-to-TM_{11} mode converter.

V. Microwave Power Combiner/Splitter

The optimized mode-control concept can be applied to combine the output signals from two or more amplifiers. The key that enables such combining relates to viewing the problem as one of mode conversion, which can be ac-

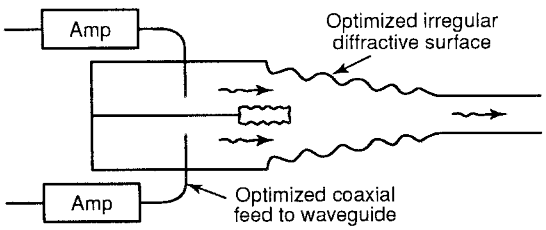

Fig. 9. Illustration of an optimized microwave power combiner, which converts the signal in two coaxial lines to a single waveguide output. The same structure connected in reverse is used as a splitter to provide the input to the amplifier modules.

complished by optimizing a waveguide control region to perform this function over the required bandwidth. Current combining approaches use large tapered structures or resonant lines, which are far from optimal and may only work reasonably well for combining two signals. By introducing more degrees of freedom and using the optimization-based mode-conversion idea, combiners which have better electrical performance and which are more flexible and compact should be possible. For example, more than two transmission lines could be combined simultaneously, and there could be better control over bandwidth and losses within specific frequency ranges.

Many antenna systems have rectangular-waveguide feed networks, while convenient packaging for solid-state power amplifiers would involve coaxial connections. Therefore, a natural initial power-combining implementation would be to combine the coaxial outputs from several amplifiers into one rectangular-waveguide output, as shown in Fig. 9. If a gain stage is needed in a rectangular-waveguide system, then the same structure used in reverse can act as a power splitter to obtain the feed signals for each amplifier. For a metal-walled waveguide with homogeneous dielectric, such as air or free space, with variations in the conducting wall profile, as illustrated in Fig. 9, a mode-matching solution can again be used conveniently. In the optimization, staircase approximations to the wall topography would be varied to maximize the combining efficiency over a prescribed frequency range. Combining more than two inputs could be achieved in sets of two, by duplicating structures similar to Fig. 9, or in a single multiple-input-to-single-output step.

In some situations, it may be desirable to integrate the amplifiers and combining network. For example, in an active-array antenna, the amplifier would ideally be located at the antenna element. Therefore, the combiner would need to be implemented using microstrip, coplanar waveguide, or a similar integrated transmission line. The concepts we have presented for mode control in metal-walled waveguides should apply. The waveguiding properties of microstrip and coplanar waveguide can be varied through changes in the conductor patterns. Abrupt discontinuities in an open structure may induce radiation, and if a large shield is used, coupling to cavity modes may occur (these are modes dictated primarily by the cavity and not the strip geometry, where the latter is the goal). However, the size of the enclosure can be made quite small using micromachined cavities, thereby reducing the number of cavity modes which can propagate and, consequently, increasing the mode control achievable by varying the strip geometry.

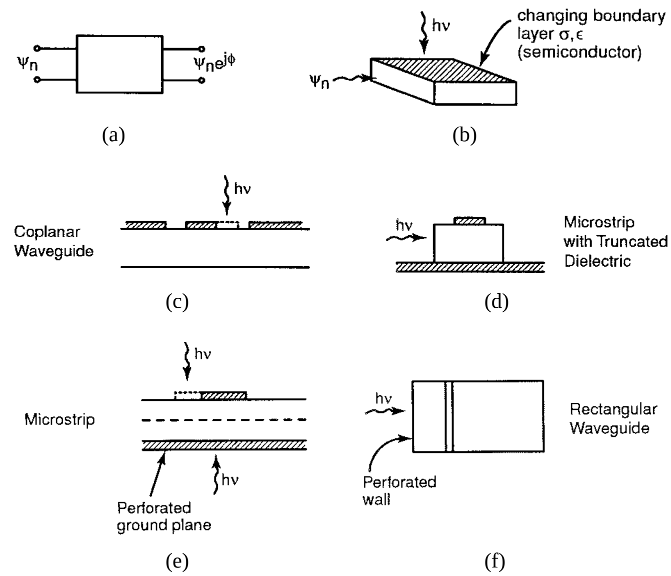

Fig. 10. Optimized phase shifters. (a) Two-port operation. (b) Use of light to modify a boundary condition or waveguide property. (c) Coplanar waveguide. (d) Microstrip with narrow dielectric. (e) Microstrip with varying conductor width or substrate thickness. (f) Rectangular waveguide with varying dimension.

VI. Microwave Phase Shifter

Achieving a fixed phase shift in a waveguide field at a particular frequency can be viewed as a field transformation, which can be accomplished using our optimized mode-control concept. For a broad-band signal, the phase-shift requirements to achieve a desirable radiation pattern in an antenna array application are more complicated, e.g., a specific frequency-dependent phase shift may be necessary. Such broad-band signals may result from a frequency-division multiplexed signal or a chirped microwave pulse, which could necessitate multiple frequencies or a variable instantaneous frequency to be dealt with. To do so, the geometry of the phase shifter must be reconfigured quickly. Consider then, the application of our optimized mode-control concept to the realization of a phase shifter in any kind of waveguide, as a replacement for switched delay lines or ferrite phase shifters [30]. With a particular mode input, usually the lowest order dominant mode, the goal is to impose a set of phase shifts with minimum loss to that mode, where this implies that coupling to other transmitted or reflected modes would be minimized. We describe how to realize a new phase shifter using mode-control concepts. It should be possible to control the phase and to do so together with filtering, coupling, or other operations.

Phase control is illustrated as a two-port operation in Fig. 10(a). Optically controlled semiconductor waveguides have been used to control the propagation characteristics of millimeter-wave signals [31], a concept illustrated in Fig. 10(b). The required phase shift could be achieved in a semiconductor waveguide whose properties are controlled optically by laser illumination through optical fibers. Unfortunately, there is loss associated with this type of phase control.

To reduce this loss, a boundary condition on a microwave waveguide could be varied, again by means of optical control, allowing the microwave signal to be primarily in a low-loss material. This would require that when above bandgap light is present, photoexcited carriers make the semiconductor metallic and, in the absence of light, the material is less conducting. By inserting such a material in a microwave waveguide, the conducting boundary could be at one of two locations, depending on whether light is present or not. This provides a mechanism for modifying the phase shift on a transmitted signal. Fig. 10(c)–(f) shows some examples. In Fig. 10(c), the width of the central conductor in the coplanar waveguide is being changed by incident light and, in Fig. 10(d), a conducting sidewall is imposed in the microstrip. Fig. 10(e) shows two ways to control microstrip properties by changing the width of the top conductor and by illuminating an embedded semiconductor layer within the substrate with light that passes through a perforated bottom conductor; two different dielectric constants could be used on either side of the semiconductor layer to form a composite substrate, giving rise to a dramatic change in effective dielectric constant. In Fig. 10(f), light passing through a perforated conductor sidewall of a rectangular waveguide illuminates a semiconductor bifurcation layer (or a small semiconductor sample located somewhere in the waveguide) to control the effective waveguide dimension or transmission properties. By defining a boundary as a series of short waveguide segments using light, these pixels could be switched from one position to the other. This binary pixel control would then be reconfigured through high-speed optical addressing for each phase-shift operation.

Unfortunately, modification in the size of the waveguide creates discontinuities. It would be necessary to achieve the required phase shift while minimizing the influence of these discontinuities, or even to utilize these discontinuities in a simultaneous task such as filtering. The design goal becomes to realize a specific set of phase shifts, while minimizing lost power. A mode-matching solution can again be employed. With small overall losses due to the semiconductor boundary, which defines one wall of the rectangular waveguide in each uniform waveguide region of the staircase structure, the loss can be incorporated through perturbation of a lossless field solution, i.e., the loss can be calculated by using waveguide mode solutions for perfectly conducting walls and then introducing the small sheet resistance represented by the semiconductor.

Rather than modifying the waveguide geometry through an optically excited semiconductor layer, it should be possible to use ferroelectric materials in a similar fashion. Again, loss is an important issue and geometries and materials that result in low loss would need to be explored.

VII. Filters and Reflectors

Dielectric filters are used in a number of microwave and many optical systems. Filters are a critical element in any optical-fiber communication system, particularly one that would use WDM. To maximize channel bandwidth utilization, it is desirable to have many closely spaced wavelengths [32].

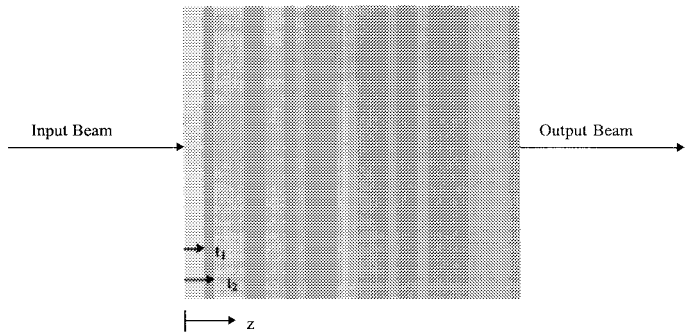

Fig. 11. An aperiodic dielectric stack filter.

It is then necessary to have very narrow-band filters that are capable of selecting one of these lines prior to detection or for amplification purposes. Dielectric waveguide filters are useful in optical communication systems, where the approach has been to use coupled periodic Bragg reflectors [33] or Bragg gratings with a perturbation consisting of an odd multiple of $\lambda/4$ spacing at some point in the periodic system to achieve a narrow passband within a stopband of the individual Bragg structures [34]. Moderate loss has been achieved using such a filter built with an X-ray mask [35]. In addition, periodic Bragg surfaces have been suggested for use in a coupled line amplifier to increase the wavelength tuning range [36].

The one-dimensional (1-D) dielectric filter is a dielectric stack. Relatively thick Bragg reflector stacks are required for a high-Q cavity in a vertical-cavity surface-emitting laser diode (VCSEL), where increased quality factor (Q) in a filter or resonator implies a narrower passband or better wavelength selectivity. These can be grown using molecular beam epitaxy (MBE) with materials having a differing refractive index, e.g., alternating layers of GaAs and $Al_xGa_{1-x}As$. Besides the time necessary to grow these reflectors, they also consume valuable material in MBE systems (many systems must be opened for material resourcing). Therefore, approaches that would result in the equivalent Q with thinner mirrors would be beneficial.

Consider the Bragg reflector or dielectric stack filter of Fig. 11. Traditional designs of the dielectric stack filter are periodic with alternating layers of two materials having different dielectric constants, resulting in a Bragg reflector. These periodic structures have a limit on the minimum bandwidth that can be achieved for the filter characteristics of the dielectric stack, given a material system and total thickness. There is a possibility to reduce the bandwidth beyond this limit if an inherent periodicity is not assumed in the material variation of the dielectric stack. The use of genetic algorithms for optimization has been suggested to search a larger domain of structures for the design of the dielectric stack [37]. However, various structures designed using this technique have not shown a significant improvement in the bandwidth of the filter. A preliminary study of the application of the SOM for the design of the dielectric stack filter has shown promise. A step-by-step procedure for designing these devices is provided in [7]. As this is a single mode problem, with fewer degrees of freedom than the waveguide problems we have considered, one may anticipate that any improvement over a periodic solution may be less spectacular.

Photonic bandgap structures have been suggested to control spontaneous emission in lasers and to realize reflectors and filters [38]–[40]. These structures are basically periodic in one, two, or three dimensions. A field solution satisfying the unit-cell boundary conditions must be of the harmonic form and, using electromagnetic nomenclature, the field is represented using Floquet modes or Bloch waves [41], [42]. In the $k-\beta$ or dispersion diagram, the infinite set of forward- and backward-traveling waves has a series of stopbands, where a propagating mode does not exist. In a lossless structure, the frequencies corresponding to these stopbands will result in evanescent fields. In the laser application, one would want the gain profile to lie within one of the stopbands and then to open up an allowed mode. This opening of a mode has been accomplished by introducing an imperfection into a periodic array, such as placing no inhomogeneity at a lattice site, or introducing a $\lambda/4$ "phase slip" [38], the same concept employed in high Q filters for WDM applications [34]. Photonic bandgap experiments have been performed in the microwave regime, where it was relatively easy to fabricate the structures [40].

Our idea of irregular mode-control regions can produce devices which are similar in function to photonic bandgap structures, but the concept is fundamentally different. The important distinction is that we are no longer restricted to the perturbation of a regular periodic system, which may not be easy to fabricate. This opens up many possibilities for designing components, which should provide better optical features.

VIII. Wavelength-Dependent Switch

Consider near-field optical diffractive structures, where the evanescent fields play a very important role in determining the complete field distribution [43]; in the far-field, the evanescent mode content contributes only to the propagating field amplitudes. Such a near-field diffraction surface could aptly be named a mesoscopic surface, where its geometry lies between the microscopic and macroscopic regimes, relative to the optical wavelength. For a WDM system, it should be possible to design better multiplexers and demultiplexers, where the latter is the same element used in reverse. By better, we mean more efficient, more compact, with more control over the beam splitting, and with a greater amenability to fabrication.

The demultiplexer is ideally a lossless, wavelength-dependent power splitter. It is important to have high-wavelength sensitivity because the overall bandwidth is limited in an optical communication system by the erbium-doped fiber amplifier bandwidth (35 nm, between 1530–1565 nm) [44], [45]. To achieve 1 nm or less between channels places stringent requirements on components. Furthermore, the undefined polarization from most optical-fiber systems requires that the multiplexers be polarization independent for low loss [46].

Consider the case of a dual-wavelength WDM system. Fig. 12(a) shows a multiplexing element which combines two input optical signals (from, e.g., two fibers) into a single output. The demultiplexing element is shown in Fig. 12(b).

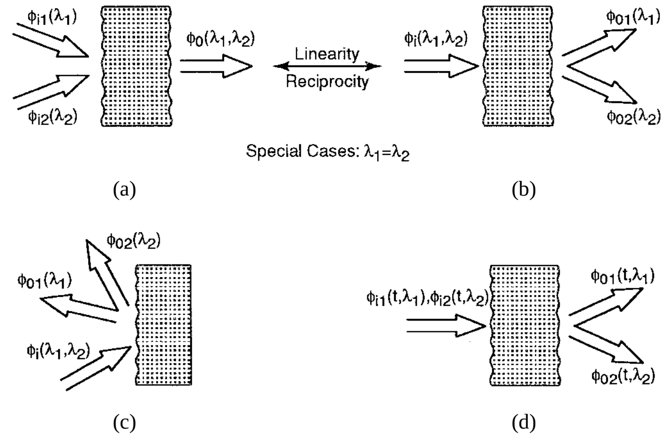

Fig. 12. An illustration of the functionality of the optimized irregular mesoscopic diffracting structures as optical multiplexers and demultiplexers or switches. (a) Transmission multiplexer. (b) Demultiplexer. (c) Reflection demultiplexer. (d) Temporal demultiplexing.

It is not necessary to know the phase relationship between the incident modes provided that the two signals have different wavelengths. This is a consequence of linearity, whereby superposition holds. If the input signals represent different modes at the same wavelength, then the phase relationship between them must be known.

The generic optimized mesoscopic diffractive elements in Fig. 12(a) and (b) are shown being operated in the transmission mode. A structure could also be designed for use in reflection, as indicated by Fig. 12(c). In addition, there could be temporal modulation, such as pulse code modulation (PCM) at each wavelength. Such a system is depicted in Fig. 12(d). In this latter case, with nanosecond switching, the spectrum is not altered significantly, thus, the diffractive surface would not be sensitive to the PCM. However, if femtosecond pulses are used, then the diffractive properties of the surface could be used to switch the signal based on the temporal (and corresponding spectral) properties of the signal.

We envision a multilayer diffractive structure which has prescribed metal or differing dielectric patterns on each layer and a specific set of separations between layers. The number of degrees of freedom in such a structure is very large: in two dimensions, the width and location of each strip on a given layer and the separation between layers and the number of layers. To reduce the number of variables, the metal strips on each layer could be periodic. This concept is shown in Fig. 13(a), where each layer has three variables, the period D, the duty cycle d/D, and the offset distance. The distance between layers and the number of layers are also variables. The strip-width variations and interlayer distances are expected to be in the 0.1λ–λ range. The geometry in Fig. 13(a) is similar to a series of cascaded parallel-plate metal-walled waveguide discontinuities with offset waveguide axes. The waveguide wall can be removed with a periodic extension of the problem (the method of images), which would result in a system much like Fig. 13(a). The structure we propose would have locally periodic layers, i.e., be periodic over a spatial support comparable to the incident optical signal (say, 5–10 λ). The general aperiodic case is shown in Fig. 13(b).

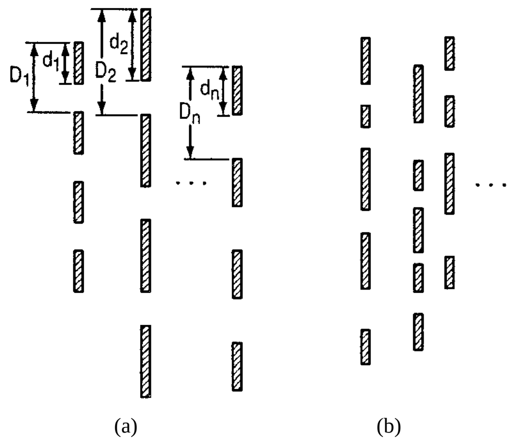

Fig. 13. Multiple-layer conducting-strip diffractive surfaces for multiplexing elements. (a) Offset periodic structure. (b) Irregular structure.

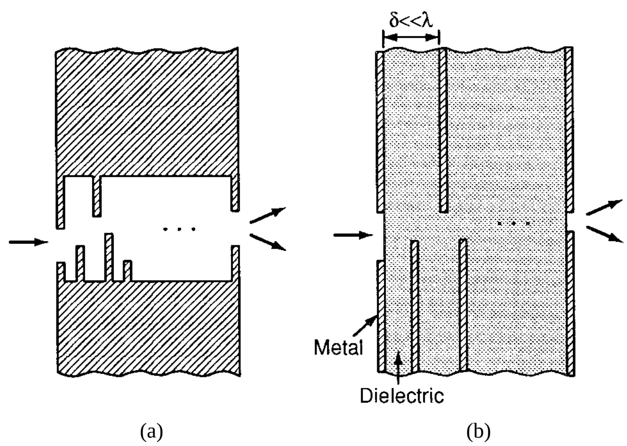

Fig. 14. A waveguide-type frequency-depdendent diffractive structure acting as a switch and its analog, which is amendable to fabrication at infrared wavelengths. (a) Waveguide-type diffractive structure. (b) Physical implementation.

Using structures like Fig. 13, the goal is with incident light at a particular angle (say, normal) with two wavelengths, to achieve a split with prescribed characteristics. The field at the two wavelengths along a line parallel to the surface at the output needs to be optimized to maximize coupling of each wavelength to one fiber (with minimal crosstalk).

The direct analogy with what we have done previously in metal-walled waveguides [2], but with more than one wavelength, is depicted in Fig. 14(a). A single-input beam or waveguide mode with two wavelengths is to be converted to two output modes or focal spots, one for each wavelength. The conducting fins have a small thickness and they are closely spaced, relative to the wavelength. The location and height of the fins and the number of fins are optimized to perform the multiplexing operation. A structure similar in function to Fig. 14(a), but which is relatively straightforward to fabricate, is shown in Fig. 14(b). Since the fins are closely spaced, propagating transverse fields will not be excited, i.e., the transverse modes will be decaying or evanescent. The boundary condition is not identical in the two cases, but achievable functionality should be equivalent.

Another implementation could use differing dielectrics rather than a metal–dielectric system. Field control will diminish as the refractive indexes become more similar.

IX. Conclusion

This paper has summarized the idea of using optimized irregular structures for mode control in microwave and optical devices. A generalized formulation of the SOM has been provided, which allows for the design of totally arbitrary structures and material compositions for field transformation in unbounded space and guided wave applications. Numerical results have been reviewed for various irregular structures, which indicate that there is a large domain of aperiodic device designs that can surpass the performance limits achieved by periodic devices. For microwave waveguides, the irregular structures provide the ability to combine more than one device into a single compact structure, such as a mode transducer and waveguide transition. Finally, the paper discussed the application of irregular structures in optical devices, specifically, the design of narrow-band dielectric stack filters and reflectors and optical switches. There is an infinite domain of irregular structures that can be utilized for mode control, and only a small subset has been explored.

The challenges in solving for the optimum mode-control structure are twofold: selecting one of a set of nonunique results, based upon desired features, and arriving at these solutions efficiently. We have previously explored parallel computer techniques for the solution of inverse problems [47], an approach that could be applied to the synthesis of field transformers to make solutions with a large number of variables more tractable. We do not need a unique solution. Rather, we desire a solution which affords a set of desirable characteristics, such as bandwidth or amenability to fabrication. This view of the nonlinear optimization problem differs from the usual, where the goal is to obtain the unique solution with sufficient accuracy. Therefore, there are many issues related to the solution for optimized mode-control elements which need to be addressed.

References

[1] T. Haq, K. J. Webb, and N. C. Gallagher, “Scattering optimization method for the design of compact mode converters for waveguides,” *IEEE Trans. Microwave Theory Tech.,* vol. 43, pp. 559–565, Mar. 1995.

[2] ——, “Compact circular waveguide mode converters,” *Microwave Opt. Technol. Lett.,* vol. 13, pp. 251–255, Dec. 1996.

[3] ——, “Synthesis of waveguide mode control devices based on aperiodic gratings,” *J. Opt. Soc. Amer. A, Opt. Image Sci.* vol. 13, pp. 1501–1505, July 1996.

[4] ——, “Aperiodic grating structure for TE_{11}–TM_{11} mode conversion,” *Proc. SPIE,* vol. 2622, pp. 196–206, 1995.

[5] ——, “Scattering optimization method for the design of compact mode converters for waveguides,” *IEEE Trans. Microwave Theory Tech.,* vol. 43, pp. 559–565, Mar. 1995.

[6] ——, “Smooth surface discretization for the design of waveguide mode converters,” in *IEEE Antennas Propagat./URSI Int. Symp.,* Baltimore, MD, June 1996.

[7] ——, “Design method for compact waveguide mode control and converter devices,” Provisional Applicat. 60/010,160, patent pending.

[8] T. Haq, “Design and fabrication of compact waveguide mode control devices,” Ph.D. dissertation, School Elect. Computer Eng., Purdue Univ., West Lafayette, IN, Aug. 1995.

[9] M. Thumm, “High-power millimeter-wave mode converters in overmoded circular waveguides using periodic wall perturbations,” *Int. J. Electron.,* vol. 57, pp. 1225–1246, 1984.

[10] J. S. Levine, “Rippled wall mode converters for circular waveguide,” *Int. J. Infrared Millim. Waves,* vol. 5, pp. 937–952, 1984.

[11] M. J. Buckley and R. J. Vernon, “Compact quasi-periodic and aperiodic $\mathrm{TE}_{\mathrm{on}}$ mode converters in overmoded circular waveguides for use with

gyrotrons," *IEEE Trans. Microwave Theory Tech.*, vol. 38, pp. 712–721, June 1990.

[12] N. F. Kovalev, I. M. Orlova, and M. I. Petelin, "Wave transformation in a multimode waveguide with corrugated walls," *Radio Phys. Quant. Electron.*, vol. 11, pp. 783–786, 1968.

[13] K. Kumrić, M. Thumm, and R. Wilhelm, "Optimization of mode converters for generating the fundamental TE_{01} mode from TE_{06} gyrotron output at 140 GHz," *Int. J. Electron.*, vol. 64, pp. 77–94, Jan. 1988.

[14] M. Thumm and H. Kumrić, "TE_{03} to TE_{01} mode converters for use with a 150 GHz gyrotron," *Int. J. Infrared Millim. Waves*, vol. 8, pp. 227–240, 1987.

[15] M. J. Buckley, D. A. Stein, and R. J. Vernon, "A single period TE_{02}–TE_{01} mode converter in a highly overmoded circular waveguide," *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 1301–1306, Aug. 1991.

[16] M. Otsuka, M. Shimizu, and M. Nishi, "Development of mode converters for 28 GHz electron cyclotron heating system," *Int. J. Electron.* vol. 70, pp. 989–1004, May 1991.

[17] D. Marcuse and R. M. Derosier, "Mode conversion caused by diameter changes of around dielectric waveguide," *Bell Syst. Tech. J.*, pp. 3217–3232, Dec. 1969.

[18] S. E. Miller, "Coupled wave theory and waveguide applications," *Bell Syst. Tech. J.*, vol. 33, pp. 661–719, May 1954.

[19] D. V. Vinogradov and G. G. Desinov, "Waveguide mode converters with step type coupling," *Int. J. Infrared Millim. Waves*, vol. 12, pp. 131–140, 1991.

[20] E. R. Nagelberg and J. Shefer, "Mode conversion in circular waveguides," *Bell Syst. Tech. J.*, pp. 1321–1338, Sept. 1965.

[21] A. Wexler, "Solution of waveguide discontinuities by modal analysis," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-15, pp. 508–517, Sept. 1967.

[22] P. J. B. Clarricoats and K. R. Slinn, "Numerical solution of waveguide discontinuity problems," *Proc. Inst. Elect. Eng.*, vol. 114, pp. 878–885, July 1967.

[23] L. Carin, K. J. Webb, and S. Weinreb, "Matched windows in circular waveguide," *IEEE Trans. Microwave Theory Tech.*, vol. 36, pp. 1359–1362, Sept. 1988.

[24] H. Patzelt and F. Arndt, "Double-plane steps in rectangular waveguides and their applications for transformers, irises, and filters," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30, pp. 771–776, May 1982.

[25] T. S. Chu and T. Itoh, "Generalized scattering matrix method for analysis of cascaded and offset microstrip step discontinuities," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-34, pp. 280–284, Feb. 1986.

[26] W. J. English, "The circular waveguide step-discontinuity mode transducer," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-21, pp. 633–636, Oct. 1973.

[27] Z. X. Zhang, G. Janzen, G. Müller, P. G. Schuller, M. Thumm, R. Wilhelm, and V. Erckmann, "Mode analysis of gyrotron radiation by far field measurements," in *8th Int. Infrared Millimeter Waves Conf. Dig.*, Miami Beach, FL, 1983.

[28] S. Silver, Ed., *Microwave Antenna Theory and Design* (MIT Radiation Laboratory Series). Boston, MA: Boston Tech. Lithographers, 1963, pp. 336–338.

[29] P. D. Potter, "A new horn antenna with suppressed sidelobes and equal beamwidths," *Microwave J.*, vol. 6, pp. 71–78, June 1963.

[30] R. J. Mailloux, "Phased array theory and technology," *Proc. IEEE*, vol. 70, pp. 246–291, Mar. 1982.

[31] A. M. Vaucher, C. D. Striffler, and C. H. Lee, "Theory of optically controlled millimeter-wave phase shifters," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-31, pp. 209–216, Feb. 1983.

[32] H. Toba, K. Oda, K. Nakanishi, N. Shibata, K. Nosu, N. Takato, and M. Fukuda, "A 100-channel optical FDM transmission/distribution at 622 mb/s over 50 km," *J. Lightwave Technol.*, vol. 8, pp. 1396–1400, Sept. 1990.

[33] R. F. Kazarinov, C. H. Henry, and N. A. Olsson, "Narrow-band resonant optical reflectors and resonant optical transformers for laser stabilization and wavelength division multiplexing," *IEEE J. Quantum Electron.*, vol. QE-23, pp. 1419–1425, Sept. 1987.

[34] H. A. Haus and Y. Lai, "Theory of cascaded quarter wave shifted distributed feedback resonators," *IEEE J. Quantum Electron.*, vol. 28, pp. 205–213, Jan. 1992.

[35] J. N. Damask, V. V. Wong, J. Ferrera, H. I. Smith, and H. A. Haus, "Highly coherent electron-beampwritten quarter-wave-shifted distributed brag resonators for channel-dropping filters," in *OFC Dig.* (OSA Tech. Dig. Series 8), Feb. 1995, pp. 225–226.

[36] M. C. Amann and S. Illek, "Tunable laser didoes utilizing transverse tuning scheme," *J. Lightwave Technol.*, vol. 11, pp. 1168–1182, July 1993.

[37] E. Michielssen, S. Ranjithan, and R. Mittra, "Spatial multilayer filter design using real coded genetic algorithms," *Proc. Inst. Elect. Eng.*, vol. 139, pt. J, pp. 413–420, Dec. 1992.

[38] E. Yablonovitch, "Photonic band-gap structures," *J. Opt. Soc. Amer. B, Opt. Phys.*, vol. 10, pp. 283–295, Feb. 1993.

[39] D. R. Smith, S. Schultz, N. Kroll, M. Sigalas, K. M. Ho, and C. M. Soukoulis, "Experimental and theoretical results for a two-dimensional metal photonic bandgap cavity," *Appl. Phys. Lett.*, vol. 65, pp. 645–647, Aug. 1994.

[40] E. Ozbay, A. Abeyta, G. Tuttle, M. Tringides, R. Biswas, C. T. Chan, C. M. Soukoulis, and K. M. Ho, "Measurement of a three-dimensional photonic band gap in a crystal structure made of dielectric rods," *Phys. Rev. B, Condens. Matter* vol. 50, pp. 1945–1948, July 1994.

[41] A. Caroglanian and K. J. Webb, "Study of curved and planar frequency selective surfaces with rectangular patches of various aspect ratios," *IEEE Trans. Antennas Propagat.*, vol. 39, pp. 211–217, Feb. 1991.

[42] C. Kittel, *Introduction to Solid State Physics.* New York: Wiley, 1986.

[43] R. Brauer and O. Bryngdahl, "From evanescent waves to specified diffraction orders," *Opt. Lett.*, vol. 22, pp. 754–756, June 1997.

[44] T. Li, "The impact of optical amplifiers on long-distance lightwave telecommunications," *Proc. IEEE*, vol. 81, pp. 1568–1579, Nov. 1993.

[45] N. S. Bergano and C. R. Davidson, "Wavelength division multiplexing in long-haul transmission systems," *J. Lightwave Technol.*, vol. 14, pp. 1299–1308, June 1996.

[46] L. H. Spiekman, M. R. Amersfoort, A. H. de Vreede, F. P. van Hamm, A. Kuntze, J. W. Pedeson, P. Demeester, and M. K. Smit, "Design and realization of polarization independent phased array wavelength demultiplexers using different array orders for TE and TM," *J. Lightwave Tech.*, vol. 14, pp. 991–995, June 1996.

[47] D. Goeckel, K. J. Webb, and N. C. Gallagher, "Massively parallel iterative determination of stratified dielectric parameters from scattered field measurements," *J. Opt. Soc. Amer. A, Opt. Image Sci.* vol. 10, pp. 1093–1100, May 1993.

Tanveer ul Haq (S'93–M'95) was born in Sargodha, Pakistan, on Feb. 5, 1962. He received the B.E. degree in avionics engineering from the College of Aeronautical Engineering, Risalpur, Pakistan, in 1983, and the M.S.E.E. and Ph.D. degrees from Purdue University, West Lafayette, IN, in the fields and optics area in 1992 and 1995, respectively.

From 1983 to 1990, he worked in the wireless communications area at a research and development center in Pakistan. He served on the faculty of the University of Delaware for the 1995–1996 academic year. He later joined Comsearch, Reston, VA, a wireless engineering consulting firm. Since August 1997, he has been with Lucent Technologies, Whippany, NJ. He has also worked at many institutions around the world, including the East China Research Institute of Electronic Engineering, Hefei, China. His research interests include design and performance engineering of personal communication systems (PCS's) and cellular systems, RF propagation modeling, inverse scattering problems, and diffractive optics. He has published several journal papers and currently has two patents pending.

Dr. ul Haq is a member of Tau Beta Pi and Eta Kappa Nu. He was the recipient of the Gold Medal for Best Engineering student of the year by the NED University of Engineering and Technology in 1983.

Kevin J. Webb (S'81–M'84–SM'98) received the B.Eng. and M.Eng. degrees from the Royal Melbourne Institute of Technology, Melbourne, Australia, in 1978 and 1981, respectively, the M.S.E.E. degree from the University of California at Santa Barbara, in 1981, and the Ph.D. degree from the University of Illinois at Urbana-Champaign, in 1984.

After five years on the faculty of the University of Maryland at College Park, he joined the School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN, in 1990.

Neal C. Gallagher (S'72–M'75–SM'85–F'87) received the Ph.D. degree from Princeton University, Princeton, NJ, in 1974.

He is the Charles Evan Black Professor and Chair of Electrical Engineering at the University of Delaware, Newark. He is currently working on the use of finite-element methods to solve electromagnetic problems, the use of rank-order filtering techniques to improve the performance of phase-locked loops, the modeling of cellular automata using wave theory, and on the autofocus problem in SAR. He was on the faculty at Purdue University for 18 years, and prior to that, was on the faculty at Case Western Reserve University. He has published in the areas of stochastic processes, quantization and source coding, electromagnetic theory and microwave components, and optics. He is currently an Editor of *Applied Optics Information Processing*.

Prof. Gallagher is a fellow of the Optical Society of America (OSA). He has held various editorial and committee positions in the IEEE, OSA, and SPIE.