

Fast Optimization of Integrated Photonic Components Using Response Correction and Local Approximation Surrogates

Adrian Bekasiewicz^{1*}, Slawomir Koziel^{1†}, and Leifur Leifsson^{2‡}

¹Reykjavik University, Iceland

²Iowa State University, USA

bekasiewicz@ru.is, koziel@ru.is, leifur@iastate.edu

Abstract

A methodology for a rapid design optimization of integrated photonic couplers is presented. The proposed technique exploits variable-fidelity electromagnetic (EM) simulation models, additive response correction for accommodating the discrepancies between the EM models of various fidelities, and local response surface approximations for a fine tuning of the final design. A specific example of a 1,555 nm coupler is considered with an optimum design obtained at a computational cost corresponding to about 24 high-fidelity EM simulations of the structure.

Keywords: Integrated photonics, EM-driven design, design optimization, directional couplers

1 Introduction

Integrated photonic components and circuits have attracted considerable attention due to their potential applications in quantum computing and global communication systems with very high data rates (Panicia and Koehl 2005; Thompson *et al.* 2011). The possibility of realizing photonic components on a silicon substrate with a silica cladding allows for their integration with conventional electrical circuits (Kaminow 2008). Furthermore, owing to high refractive index contrast, low losses can be achieved within the waveguide, as well as compact designs (Morino *et al.* 2014; Littlejohns *et al.* 2011). One of the simplest, yet fundamental types, of integrated photonic components are directional couplers. Coupler structures have numerous applications in, among others, Mach-Zehnder

* Engineering Optimization & Modeling Center, School of Science and Engineering

† Engineering Optimization & Modeling Center, School of Science and Engineering

‡ Department of Aerospace Engineering

interferometers (Doerr *et al.* 2005; Petousi *et al.* 2015), filters (Yu *et al.* 2011; Zhang and Pan 2013), and switches (de Valicourt *et al.* 2014; Krishnamurthy *et al.* 2014).

The electrical performance of integrated photonic circuits is determined by their topology and the values of relevant geometry and material parameters (Koziel and Ogurtsov, 2013; Koziel and Ogurtsov, 2014; Mansoor *et al.* 2014). Accurate evaluation of integrated photonic circuits requires high-fidelity electromagnetic (EM) analysis, which is computationally very expensive. Even for simple components, simulation times may be as long as several hours, which make a simulation-driven design process extremely challenging. In particular, the adjustment of geometry parameters by means of a direct numerical optimization of EM simulation models is normally prohibitive when using conventional algorithms, both gradient-based (Nocedal and Wright, 2006) and derivative-free (Conn *et al.* 2009).

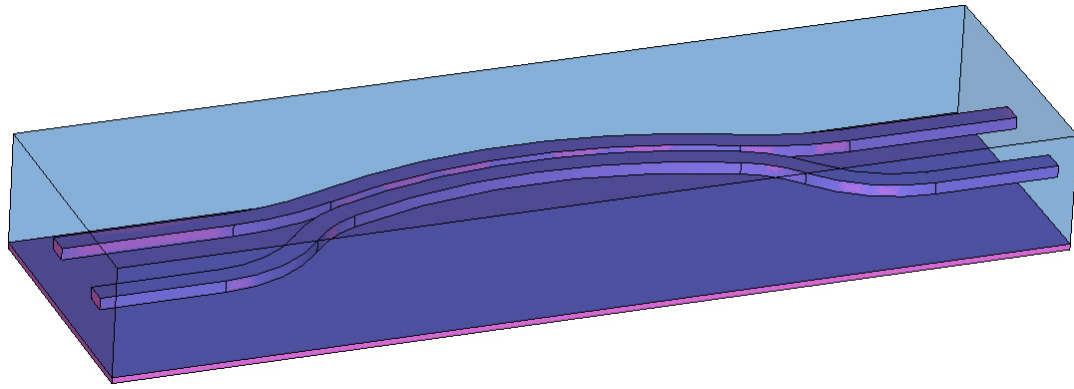
Computationally efficient simulation-driven design of simple photonic components was presented in (Koziel and Ogurtsov, 2013), where variable-fidelity EM simulations were utilized to speed up the design process. A feature-based optimization of integrated photonic microring was demonstrated in (Koziel and Ogurtsov, 2014), based on single-fidelity EM models. It turns out that, even for relatively simple components, the correlation between the low- and high-fidelity EM-simulation models may be rather poor (Koziel and Ogurtsov, 2014), which hinders—to some extent—the use of variable-fidelity simulations in the design process of photonic components.

In this paper, we demonstrate the use of variable-fidelity EM simulations for rapid design of a photonic coupler structure. Due to a limited correlation between the models of various fidelities, a low-fidelity EM model is only used at the initial stages of the search process. The coupler design is subsequently fine-tuned using a local response surface model constructed from high-fidelity EM model data only. Our methodology is illustrated using a broadband coupler designed for a C band transmission window (Oh and Paek, 2012). The final design satisfying the prescribed performance requirements is obtained at an overall computational cost corresponding to about 24 high-fidelity EM simulations of the structure.

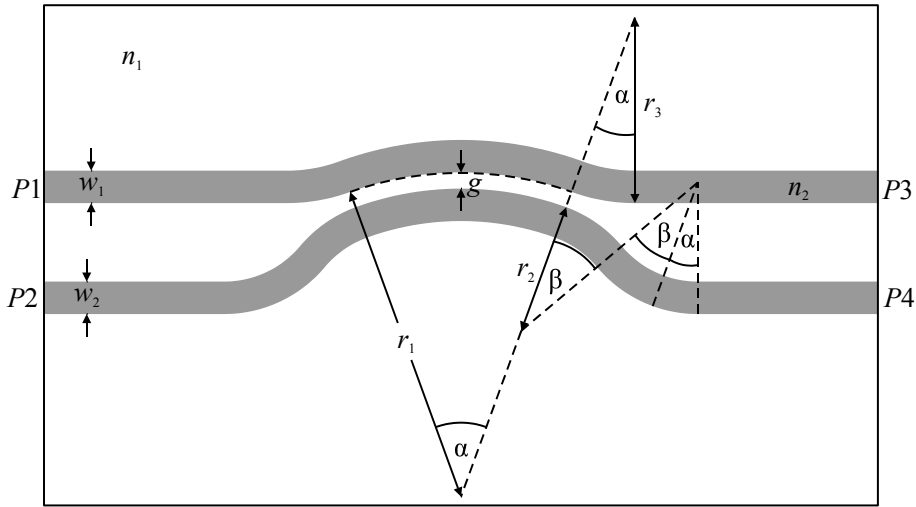
2 Integrated Photonic Components: Models and Design Challenges

Consider an integrated photonic 2×2 directional coupler based on a design of Morino *et al.* (2014). The structure is a four-port device with two waveguide cores arranged parallel in proximity with each other. The coupler exhibits wavelength independent operation, which is introduced by the utilization of a circular shape coupling section. The circuit is composed of a two silicon waveguide cores with the refractive index of $n_1 = 3.476$. Both cores are buried within silicon dioxide—or a so-called silica—with the refractive index of $n_2 = 1.444$. The entire structure is allocated on a thin silicon substrate. It should be noted that high difference in refractive indexes of the coupler allows for strong confinement of the light beam within the core waveguides. Therefore, the former may be constructed using low radius bends without considerable losses, and, thus, allowing for the utilization of the structure with highly integrated devices (Morino *et al.* 2014; Tsuchizawa *et al.* 2005; Yamada *et al.* 2005). Geometry of the discussed integrated coupler including its visualization, top- and cross-view, as well as detailed dimensions, are shown in Fig. 1. The structure operates as follows: a light beam is introduced to $P1$ and transmitted to $P2$. Simultaneously, short distance between waveguide cores results in coupling of the signal to $P3$, whereas $P4$ remains isolated.

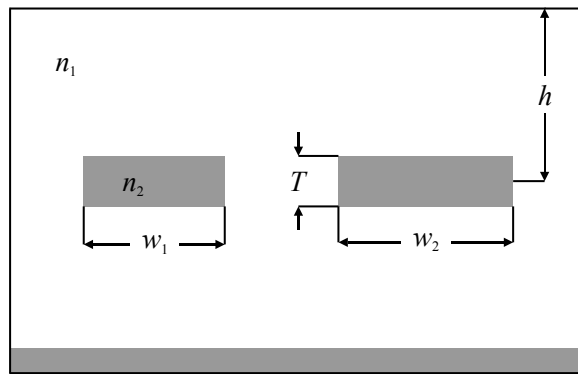
The coupler is parameterized using the following set of independent design variables: $\mathbf{x} = [r_1 \ \alpha \ \beta \ g \ T \ w_1]^T$. Additionally, we assume $r_2 = r_1/(2 \cdot \cos \alpha)$, $r_3 = r_2/\cos \beta$, $w_2 = w_1$, whereas $h = 0.5$ remains fixed. All dimensions except α and β , which are expressed in degrees, are in μm (see Fig. 1b-c). It should be noted that β is set as a variable to minimize the influence of the feed lines bending losses on a circuit operation (Hill *et al.* 2003).



(a)



(b)



(c)

Figure 1: Integrated curved photonic directional coupler (Morino *et al.* 2014): (a) visualization; (b) top view with detailed dimensions - P1, P2 P4 and P4 are the respective ports of the circuit; (c) cross-view; n_1 and n_2 stand for the refractive indices of cladding (white) and waveguide core (gray), respectively.

In a contrary to (Morino *et al.* 2014), where theoretical studies on a coupler have been performed using its two-dimensional representation, we have performed the design using a fully three-dimensional electromagnetic model. Optimization of a structure in such a setting is considerably more challenging than in the two-dimensional one, because evaluation of a reliable model is very time consuming. In order to perform the coupler design in a reasonable time-frame, its low-fidelity electromagnetic model has been prepared. The model is constructed using $\sim 1,050,000$ mesh cells and its average simulation time is about 22 min. Although the low-fidelity representation of a photonic coupler is fast, it suffers from response inaccuracy. This is accounted in a surrogate-based optimization scheme that utilizes high-fidelity model simulations. The latter is composed of roughly 20 million cells (with a simulation time ~ 8.17 h). Both designs are constructed in CST Microwave Studio and simulated using its time domain solver (CST, 2013). The design objective is to achieve equal power split for a C band transmission window, i.e., 3 dB coupling within 1,530 to 1,565 μm wavelength of interest.

3 Optimization Using Response Correction and Local Approximation Surrogates

In this section, we formulate the optimization problem and outline the proposed solution approach. The two main stages of the design process is surrogate-based optimization (Koziel and Leifsson, 2013; Queipo *et al.* 2005) involving a low-fidelity model obtained from coarse-discretization EM simulations of the coupler structure enhanced through additive response correction, as well as the tuning stage exploiting a local response surface approximation model. Numerical results obtained for the example coupler structure of Section 2 are presented in Section 4.

3.1 Problem Formulation and Objective Function

The design problem is formulated as a nonlinear minimization task of the form

$$\mathbf{x}^* = \arg \min_{\mathbf{x}} U(\mathbf{R}_f(\mathbf{x})) \quad (1)$$

where $\mathbf{R}_f$ is the high-fidelity coupler model, $\mathbf{x}$ is the vector of adjustable geometry parameters, whereas U is the objective function. In this work, we aim at obtaining equal power split within certain range of wavelengths of interest $\lambda_{\min}$ to $\lambda_{\max}$ and within certain assumed tolerance Δs . The objective function is therefore defined as

$$U(\mathbf{R}_f(\mathbf{x})) = \max_{\lambda} \{ \lambda_{\min} \leq \lambda \leq \lambda_{\max} : ||S_{21}(\mathbf{x}; \lambda)| - |S_{31}(\mathbf{x}; \lambda)|| \} \quad (2)$$

Acceptable designs are those for which $U(\mathbf{R}_f(\mathbf{x}))$ does not exceed Δs .

3.2 Design Methodology I: Surrogate-Based Optimization Using Variable-Fidelity EM Simulations and Response Correction

Because the high-fidelity EM simulations of the photonic components are computationally expensive, their direct optimization (a straightforward attempts to solve (2)), in particular, may not be practical. Here, we use a coarse-discretization version of $\mathbf{R}_f$, referred to as the low-fidelity model $\mathbf{R}_c$, to

speed up the design process. In particular, we replace the direct solution of (2) by an iterative process defined as (Bandler *et al.* 2004; Koziel *et al.* 2008)

$$\mathbf{x}^{(i+1)} = \arg \min_{\mathbf{x}} U(\mathbf{R}_s^{(i)}(\mathbf{x})) \quad (3)$$

where $\mathbf{x}^{(i)}$, $i = 0, 1, \dots$, is a sequence of approximate solutions to (2); $\mathbf{x}^{(0)}$ is the initial design. $\mathbf{R}_s^{(i)}$ is the surrogate model at iteration i , which is constructed using a simple additive response correction of the form:

$$\mathbf{R}_s^{(i)}(\mathbf{x}) = \mathbf{R}_c(\mathbf{x}) + [\mathbf{R}_f(\mathbf{x}^{(i)}) - \mathbf{R}_c(\mathbf{x}^{(i)})] \quad (4)$$

The correction term in (4) ensures a perfect matching—zero-order consistency (Alexandrov *et al.* 2001; Bekasiewicz *et al.* 2014)—between the surrogate and the high-fidelity model at $\mathbf{x}^{(i)}$, i.e., $\mathbf{R}_s^{(i)}(\mathbf{x}^{(i)}) = \mathbf{R}_f(\mathbf{x}^{(i)})$. This simple way of constructing the surrogate model is sufficient in our case due to relatively flat responses of the coupler (cf. Fig. 2). Because the particular relationships between the low- and high-fidelity model responses are generally design dependent, the process (3), (4) has to be iterated.

The first stage of the optimization process is continued until the subsequent iterations result in the improvement of the high-fidelity objective function, i.e., $U(\mathbf{R}_f(\mathbf{x}^{(i+1)})) < U(\mathbf{R}_f(\mathbf{x}^{(i)}))$. In practice, because of limited correlations between the low- and high-fidelity models, one may expect a few successful iterations (3)-(4).

3.3 Design Methodology II: Fine Tuning Using Local Approximation Models

The fine tuning of the coupler is realized using the following second-order polynomial model established in the vicinity of the design obtained in the first stage:

$$\mathbf{p}(\mathbf{x}) = \mathbf{p}([x_1 \dots x_n]^T) = p_0 + \sum_{k=1}^n p_k x_k + \sum_{k=1}^n p_{n+k} x_k^2 \quad (5)$$

where x_k is the k th components of the parameter vector $\mathbf{x}$. The model $\mathbf{p}$ is set up using $2n + 1$ evaluations of the high-fidelity model at the design obtained at the first stage of the process and $2n$ perturbed designs (up and down with respect to each of its components). The model parameters can be obtained analytically by solving an appropriate linear regression problem.

The final design is obtained simply by optimizing the model $\mathbf{p}$ using the original objective function (2). The model optimization is carried out within the region defined by the perturbations utilized to get the training data.

4 Results and Discussion

The technique described in Section 2 has been utilized to optimize the coupler structure of Section 2. The operating wavelength is 1,550 nm. The assumed tolerance for the power split is $\Delta s = \pm 0.1$ dB for the wavelength range $\lambda_{\min} = 1,530$ nm to $\lambda_{\max} = 1,565$ nm. The initial design is $\mathbf{x}^{(0)} = [18 \ 28 \ 13 \ 0.18 \ 0.21 \ 0.38]^T$. The final design $\mathbf{x}^* = [19 \ 29 \ 14.9 \ 0.17 \ 0.2067 \ 0.38]^T$ was obtained after three iterations of the initial stage (cf. (3), (4)), and the tuning stage of Section 3.3. A single iteration (3) requires (on average) 50 evaluations of the low-fidelity model and one evaluation of the high-fidelity model. Only approximate optimum of the surrogate model is obtained in each iteration in order to

reduce the computational cost of the process. A pattern search algorithm (Kolda *et al.* 2003) is utilized as an optimization engine in this stage. The routine utilizes a simple mechanism that seeks the next candidate solution by moving along the predefined grid. For more detailed description of the algorithm see (Koziel, 2010). Figure 2 illustrates low- and high-fidelity model responses at the initial design. High-fidelity model responses before and after the tuning stage are shown in Fig. 3. The range of wavelengths for which the power split imbalance does not exceed the prescribed tolerance is 42 nm and it is preserved from 1,530 to 1,572 nm. It should be noted that the obtained range is 20% larger than the required one.

The optimized curved coupler has been compared in terms of the wavelength range with a conventional state-of-the-art design of (Bekasiewicz and Koziel, 2015). The latter has been designated to operate on 1,538 nm thus direct comparison may be conducted. The range of wavelength with assumed 0.2 dB power imbalance for conventional structure is only 8 nm and it varies from 1,535 to 1,543 nm, which means that its scope of operation is over 5 times narrower than for the curved design.

The total design cost corresponds to about 24 high-fidelity simulations of the coupler structure and it includes: 150 R_c simulations for surrogate-based optimization, as well as 4 R_f and 13 R_f simulations for the low-fidelity model correction and the structure fine tuning, respectively. The detailed cost breakdown is shown in Table 1. The results obtained indicate the applicability of surrogate-based optimization for fast and reliable design of integrated photonic couplers using their complex, yet accurate three-dimensional models. It should be noted that the computational cost of design optimization may be considerably reduced by means of distributed computing. The estimated cost of algorithm operation using parallel computations corresponds to 6 R_f and 1 R_f for the stage one and two, respectively.

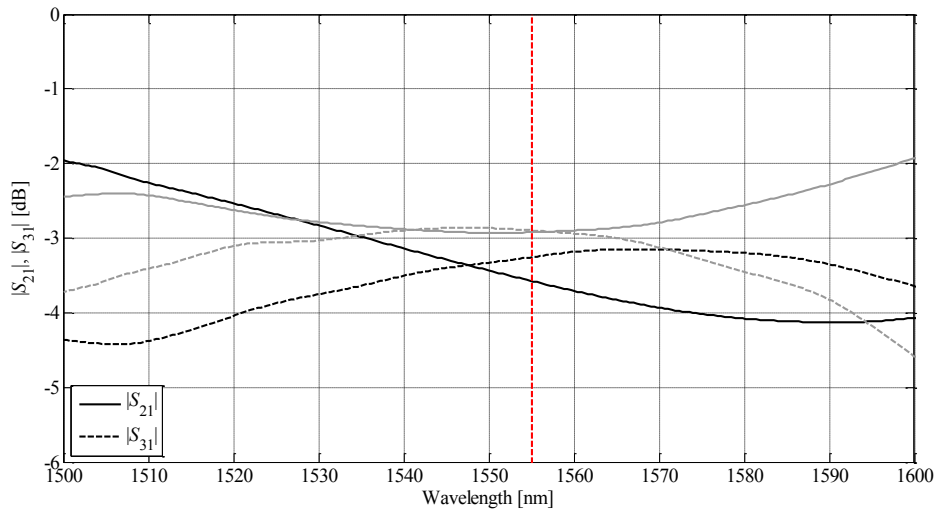


Figure 2: High- (black lines) and low-fidelity (gray lines) EM coupler models at the initial design (approximate optimum of the low-fidelity model). Operating wavelength denoted using a dashed vertical line.

Table 1: Breakdown of the design and optimization cost.

Optimization Stage	Number of model evaluations	Computational Cost	
		Absolute [h]	Relative to R_f
Surrogate-based optimization with response correction	$150 \times R_c$	55	6.7
	$4 \times R_f$	32.7	4.0
Design fine-tuning	$13 \times R_f$	106.2	13.0
Total cost	N/A	193.9	23.7

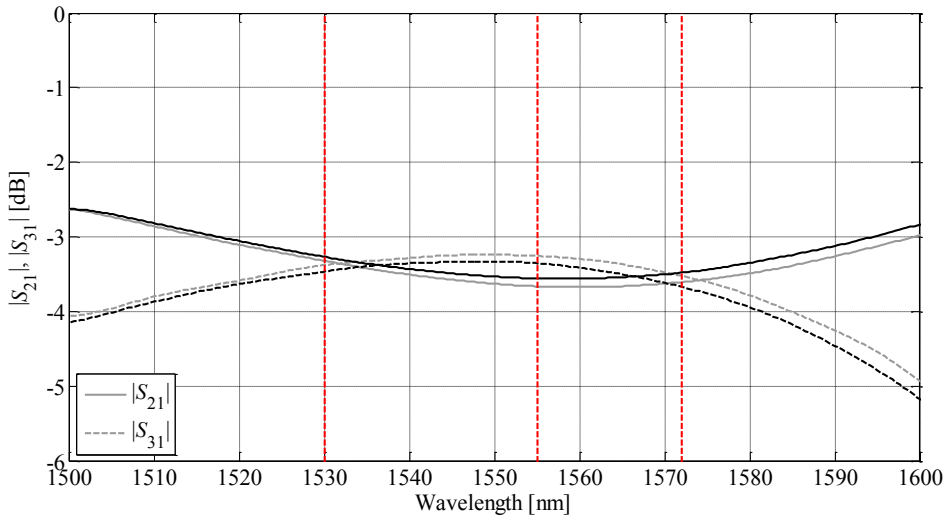


Figure 3: High-fidelity EM coupler model at the end of the first stage of the optimization process (gray lines), and at the final design (black lines). Operating wavelength and the 0.2 dB power split wavelengths marked using dashed vertical lines. The range of wavelengths corresponding to equal power split within ± 0.1 dB tolerance is 1,530 nm to 1,572 nm.

5 Conclusion

A time-wise feasible simulation-driven design optimization of integrated photonic couplers has been presented. The proposed approach is a two-stage process with the first stage exploiting variable-fidelity electromagnetic simulations of the coupler structure as well as response correction aimed at reducing misalignment between the models of various fidelities. The second stage is a fine-tuning procedure that utilizes a local response surface approximation model of the coupler. The results obtained for an example coupler indicate that the optimized design can be obtained at the reasonable computational cost (here, corresponding to about 24 simulations of the coupler at fine discretization). Future work will be focused on the application of the discussed algorithms to more complex integrated photonic structures.

References

- Alexandrov, N.M., and Lewis, R.M. (2001) *An overview of first-order model management for engineering optimization*. Optimization Eng., 2, pp. 413-430.
- Bandler, J.W., Cheng, Q.S., Dakrouy, S.A., Mohamed, A.S., Bakr, M.H., Madsen, K., Søndergaard, J. (2004) *Space mapping: the state of the art*. IEEE Trans. Microwave Theory Tech., 52, 337-361.
- Bekasiewicz, A., Koziel, S., Zieniutycz, W. (2014a) *Design Space Reduction for Expedited Multi-Objective Design Optimization of Antennas in Highly-Dimensional Spaces*. In: Koziel, S., Leifsson, L., Yang, X.S. (eds.) Solving Computationally Expensive Engineering Problems: Methods and Applications, pp. 113-147, Springer.
- Bekasiewicz, A., Koziel, S. (2015) *Rapid Simulation-Driven Design Optimization of Photonic Directional Couplers Using Variable-Fidelity EM Simulations*, Int. Rev. Prog. Applied Comp. Electromagnetics, to appear.
- Conn, A.R., Scheinberg, K., Vicente, L.N. (2009) *Introduction to Derivative-Free Optimization*. MPS-SIAM Series on Optimization.
- CST Microwave Studio (2013). Computer Simulation Technology AG, Bad Nauheimer Str. 19, D-64289 Darmstadt, Germany.
- de Valicourt, G., Moroz, N.D., Jenneve, P., Vacondio, F., Duan, G.H., Jany, C., Lelievre, A., Accard, A., Antona, J.C. (2014) *A Next-Generation Optical Packet-Switching Node Based on Hybrid III-V/Silicon Optical Gates*. IEEE Photonics Technology Lett. 26, pp. 678-681.
- Doerr, C.R., Cappuzzo, M., Chen, E., Wong-Foy, A., Gomez, L., Griffin, A., Buhl, L. (2005) *Bending of a planar lightwave circuit 2×2 coupler to desensitize it to wavelength, polarization, and fabrication changes*. IEEE Photonics Technology Lett. 17, pp. 1211-1213.
- Hill, M.T., Leijtens, X.J.M., Khoe, G.D., Smit, M.K. (2003) *Optimizing imbalance and loss in 2x23-dB multimode interference couplers via access waveguide width*. J. Lightwave Technology. 21, pp. 2305-2313.
- Kaminow, I.P. (2008) *Optical Integrated Circuits: A Personal Perspective*. J. Lightwave Technology. 26, pp. 994-1004.
- Kolda, T.G., Lewis, R.M., and Torczon, V. (2003) *Optimization by direct search: new perspectives on some classical and modern methods*. SIAM Review, 45, pp. 385-482.
- Koziel, S., Cheng, Q.S., Bandler, J.W. (2008) *Space mapping*. IEEE Microwave Magazine, 9, pp. 105-122.
- S. Koziel, (2010) *Multi-fidelity multi-grid design optimization of planar microwave structures with Sonnet*. Int. Review Prog. Applied Comp. Electromagnetics, pp. 719-724.
- S. Koziel and L. Leifsson (Eds.), (2013) *Surrogate-based modeling and optimization: applications in engineering*. Springer, New York.
- Koziel, S., Ogurtsov, S. (2013) *Multimode interference power divider design optimization using simulation-based surrogate models and space mapping*. Int. Conf. Electromagnetics Advanced App. pp. 151-154.
- Koziel, S., Ogurtsov, S. (2015) *Fast simulation-driven design of integrated photonic components using surrogate models*. IET Microwaves, Antennas Prop. to appear.
- Krishnamurthy, V., Chen, Y., Wang, Q. (2014) *MZI-Semiconductor-Based All-Optical Switch With Switching Gain*. J. Lightwave Technology. 32, pp. 2433-2439.
- Littlejohns, C.G., Youfang H., Gardes, F.Y., Thomson, D.J., Reynolds, S.A., Mashanovich, G.Z., Reed, G.T. (2014) *50 Gb/s Silicon Photonics Receiver With Low Insertion Loss*. IEEE Photonics Technology Lett. 26, pp. 714-717.
- Mansoor, R., Koziel, S., Sasse, H., Duffy, A. (2014) *Crosstalk suppression bandwidth optimization of a vertically coupled ring resonator add/drop filter*. IET Optoelectronics, to appear.

- Morino, H., Maruyama, T., Iiyama, K. (2014) *Reduction of Wavelength Dependence of Coupling Characteristics Using Si Optical Waveguide Curved Directional Coupler*. J. Lightwave Technology. 32, pp. 2188-2192.
- Nocedal, J., Wright, S.J. (2006) *Numerical Optimization*, 2nd edition, Springer, New York.
- Oh, K., Paek, U.-C. (2012) *Silica optical fiber technology for devices and components, design, fabrication, and international standards*. John Wiley & Sons, Hoboken.
- Panicia, M., Koehl, S. (2005) *The silicon solution [silicon photonics]*. IEEE Spectrum. 42, pp. 38-43.
- Petousi, D., Zimmermann, L., Gajda, A., Kroh, M., Voigt, K., Winzer, G., Tillack, B., Petermann, K. (2015) *Analysis of Optical and Electrical Tradeoffs of Traveling-Wave Depletion-Type Si Mach-Zehnder Modulators for High-Speed Operation*. IEEE J. Selected Topics in Quantum Electronics. 21, pp. 1-8.
- Queipo, N.V., Haftka, R.T., Shyy, W., Goel, T., Vaidynathan, R., Tucker, P.K. (2005) *Surrogate based analysis and optimization*. Prog. Aerospace Sci. 41, pp. 1-28.
- Thompson, M.G., Politi, A., Matthews, J., O'Brien, J.L. (2011) *Integrated waveguide circuits for optical quantum computing*. IET Circuits, Devices & Systems. 5, pp. 94-102.
- Tsuchizawa, T., Yamada, K., Fukuda, H., Watanabe, T., Takahashi, J., Talahashi, M., Shoji, T., Tamechika, E., Itabashi, S., Morita, H., *Microphotonics devices based on silicon microfabrication technology*. IEEE J. Selected Topics in Quantum Electronics. 11, pp. 232-240.
- Yamada, H., Chu, T., Ishida, S., Arakawa, Y. (2005) *Optical directional coupler based on Si-wire waveguide*. IEEE Photonics Technology Lett., 17, pp. 585-587.
- Yu Y., Dong, J., Xu, E., Li, X., Zhou, L., Wang, F., Zhang, X. (2011) *Single Passband Microwave Photonic Filter With Continuous Wideband Tunability Based on Electro-Optic Phase Modulator and Fabry-Pérot Semiconductor Optical Amplifier*. J. Lightwave Technology. 29, pp. 3542-3550.
- Zhang, Y., Pan, S. (2013) *Complex Coefficient Microwave Photonic Filter Using a Polarization-Modulator-Based Phase Shifter*. IEEE Photonics Technology Lett. 25, pp. 187-189.