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Microring-Based Wavelength Routing Matrix

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Abstract: We introduce a passive wavelength routing matrix based on microring resonators for optical packet switching architectures. We assess its technological feasibility, and its physical scalability, which is limited by the coherent crosstalk accumulation.

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1. Introduction

Photonic technologies may help overcoming the intrinsic limitations of electronics when used in interconnects, short-distance transmissions and switching operations. A promising approach to realize an optical fabric for burst or packet switching is to use a passive wavelength routing device with Tunable Transmitters (TTx) at inputs and Wideband Burst Mode Receivers (WBMR) at outputs. $N \times N$ Arrayed Waveguide Gratings (AWGs) offer a mature and commercially available solution for passive wavelength routing in Wavelength Division Multiplexing (WDM) systems. However, due to the reuse of the same wavelength by several TTx, AWGs show a limited physical scalability in terms of the number of input/output ports (in practice less than 20) [1], because of the Accumulation of Coherent Crosstalk (ACC). This drawback can be mitigated either *i*) by employing a proper scheduling algorithm or *ii*) by exploiting the periodicity of the AWG Transfer Function (TF). However, the former solution increases complexity, while the latter is viable only for small interconnects because the AWG TF is uniform only over few periods.

Among the emerging optical devices, MicroRing Resonators (MRRs) offer a promising solution for many applications. MRRs are compatible with CMOS technology, and present a periodic TF which permits to handle up to tens of channels in the ITU grid, i.e., their TF is almost constant over a wide band spectrum [2]. However, the periodicity of the MRR's TF is related to the MRR physical dimensions: the larger the TF period, the smaller the MRR radius. Thus, large periods might result in unfeasible MRRs due to current technology limitations, which prevent the feasibility of small MRR geometries. The paper major contributions are:¹ *i*) the introduction of a MRR-based passive Wavelength Routing Matrix (WRM) logically equivalent to an $N \times N$ AWG; *ii*) an analysis of its ACC and the proposal of two solutions exploiting the periodicity of the MRR TF to mitigate the ACC; *iii*) considering geometrical limitations we propose a new MRR design strategy that employs feasible MRRs to build WRMs supporting a large number of ports.

2. The microring resonator basic routing element

Fig. 1 shows the MRR-based 1×2 Switching Element (1×2 -SE). The 1×2 -SE is the basic building block of our WRM and it consists of a waveguide bent into itself and side-coupled to two perpendicular waveguides. Input optical signals are coupled into the ring and, thus, to the drop port, if their frequencies match the MRR's resonance frequencies, given by $f_x = \{m \frac{c}{2\pi R n_g} : m \in \mathbb{Z}^+\}$ [3], where m is an integer number, R is the MRR radius, n_g is the waveguide group refractive index and c is the speed of light in vacuum. For instance, in Fig. 1, $f_x = \{f_0, f_4\}$. Conversely, if the signals' frequencies are different from f_x , they continue, almost unaffected, to the through port.

MRRs, like other resonant structures, present a periodic TF, whose period is named Free Spectral Range (FSR) and depends on the geometry of the MRR, as $FSR = \frac{c}{2\pi n_g R}$ [3]. Finally, being a filtering device, the MRR is characterized by its passband (BW), commonly called *full width half maximum* bandwidth and defined as the bandwidth where input signals suffer at most a 3dB power drop with respect to the maximum of the TF. The BW depends on the coupling coefficients between the ring and the other waveguides and it can be set as a design target [3].

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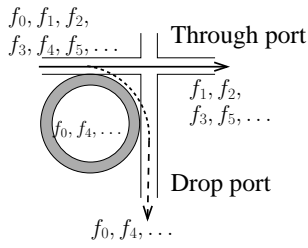


Fig. 1: 1×2 -SE

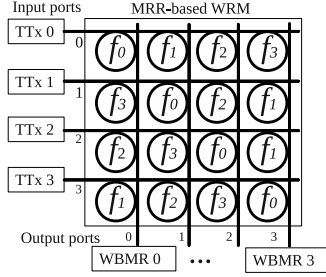


Fig. 2: 4×4 WRM based on MRR

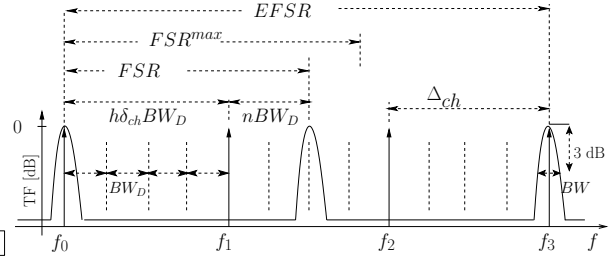


Fig. 3: TF at the drop port of the 1×2 -SE

3. The Microring-based Routing Matrix

We propose a WRM logically equivalent to an AWG. Without loss of generality, we assume a $N \times N$ WRM with synchronous and time-slotted operation, controlled by a proper scheduling algorithm. Each input port is equipped with a TTx and each output port with a WBMR, as depicted in Fig. 2. The 1×2 -SEs composing the WRM are devised such that the 1×2 -SE in position (i, j) resonates on $f_k + mFSR$, being m a positive integer equal for all the MRRs and f_k appearing at most once in each row and each column. As in typical AWGs, and with no loss of generality, we assume that f_k is selected according to $k = (j - i) \bmod N$. Finally, let w be the *fundamental* TTx tuning range, i.e., the *minimum* bandwidth through which TTxs must be able to sweep to provide full connectivity. Since each TTx must be able to tune over at least N distinct channels (at least one for each destination), $w = N\Delta_{ch}$ Hz. Finally, given that f_k cannot be repeated for each column and row, $FSR \geq N\Delta_{ch}$.

Crosstalk Analysis. Let us denote by X the maximum number of times an optical channel is used considering a complete input-output permutation (all inputs transmitting to a different output). X is a simplified measure of the ACC. Due to space limitations, we do not present a detailed physical-layer analysis, but the methodology presented in [4] can be easily exploited. The results presented in [4] showed that the scalability of MRR-based fabrics is mainly limited by the ACC. Thus, X provides a good insight on the scalability of the presented WRM. X can be reduced exploiting the periodicity of the MRR TF through the *expansion* strategy which consists in increasing the TTx tuning range. Note that a TTx could tune over a bandwidth larger than w , defined as the expanded TTx tuning range $W \geq w$. Define the TTx expansion factor $K = \{1, 2, \dots, N\}$, such that $W = Kw = KN\Delta_{ch}$ Hz. As K increases, the number of times an optical channel is reused decreases as $X = \lceil \frac{N}{K} \rceil$. Thus, if $K = 2$, $X = \lceil \frac{N}{2} \rceil$ because TTxs can use 2 channels to reach each output. However, since the tuning range might become a limiting factor if it grows too high, we further propose the *juxtaposition* strategy, which consists in using TTxs which can tune over different and disjoint tuning ranges of size w . Let L be the number of different and disjoint fundamental tuning ranges over which TTxs can tune. If the TTxs are uniformly divided into L sets, the ACC decreases as $X = \lceil \frac{N}{LK} \rceil$. Note that, the two strategies can be combined together to reduce the ACC to $X = \lceil \frac{N}{LK} \rceil$ and that they do not influence the design of the MRR TF, which still requires a $FSR \geq N\Delta_{ch}$.

4. Feasibility Analysis

Depending on the filtering quality of the MRR's TF, the proposed WRM can tolerate different values of X . Indeed, in [4] we showed that a 50×50 MRR-based crossbar is feasible using a single optical channel ($X = 50$). Furthermore, the above proposed ACC reducing strategies, can enhance the physical scalability. In this context, the main limitations arise when considering the MRR geometry. Indeed, MRRs used in the proposed WRM are required to support a $FSR \geq N\Delta_{ch}$ but, as Sec. 2 shows, $FSR \propto 1/R$. As an example, if we consider a WRM with $N = 25$ ports and a channel spacing of $\Delta_{ch} = 100$ GHz on the DWDM ITU grid, then $FSR \geq 2.5$ THz, which approximatively corresponds to a radius $R \leq 12.7 \mu\text{m}$, considering $n_g = 1.5$ (typical of Silicon waveguides) and $f_x = 195.9$ THz (the first frequency of the conventional C band of the ITU grid). Note that a radius of few μm is close to current technological limits [5]. Indeed, radii of hundreds of μm are more common, as a small radius implies high losses in traversing the ring waveguide because of the poor confinement of optical signals [3]. As such, the minimum feasible MRR radius R_{\min} implies a maximum achievable FSR, FSR^{\max} , and a maximum of $N^{\max} < FSR^{\max}/\Delta_{ch}$ ports. Hence, when the limitations on the MRR size are considered, the maximum number of ports that the proposed WRM supports is around 10.

This limitation can be mitigated by carefully designing the MRR TF. For instance, let us assume that $FSR = 2\Delta_{ch}$. Thus, one channel among the two available is dropped within the MRR's TF period, and the maximum achievable number of ports is $N^{\max} = 2$. Instead, if we design MRRs to present a $FSR = 3/2\Delta_{ch}$ (as in Fig. 3 the peaks of the MRR TF coincide with channels at f_0 and f_3). Therefore, N^{\max} becomes 3. In this case we say that the MRR offers an equivalent FSR, $EFSR = 3\Delta_{ch}$. Let $BW_D \geq BW$ be the minimum MRR bandwidth able to divide Δ_{ch} a finite number of times δ_{ch} ,

Table 1. Capacity and design constraints for different MRR Radius and channels plans

R_{\min} [μm]	Δ_{ch} [GHz]		
$R_b = 10\text{Gbps}$	200	100	50
5	3180 (9.94)	3180 (4.97)	2530 (1.99)
10	1590 (9.94)	1590 (4.97)	1270 (1.98)
100	150 (7.5)	140 (4.67)	110 (1.83)
$R_b = 40\text{Gbps}$			
5	2520 (1.97)	2520 (1)	0 (0)
10	1240 (1.94)	1240 (1)	0 (0)
100	120 (1.5)	120 (1)	0 (0)

 (a) Aggregate capacity in Gbps for different MRR R_{\min} and Δ_{ch} using *EFSR*. Values in parenthesis report the gain with respect to a classic WRM.

R_{\min} [μm]	Δ_{ch} [GHz]		
$R_b = 10\text{Gbps}$	200	100	50
5	-	31.8 (7)	12.65 (6)
10	31.8 (4)	15.9 (4)	6.35 (3)
100	3 (1)	1.4 (1)	0.55 (1)
$R_b = 40\text{Gbps}$			
5	12.6 (2)	6.3 (2)	0 (-)
10	6.2 (1)	3.1 (1)	0 (-)
100	0.6 (1)	0.3 (1)	0 (-)

 (b) TTx tuning range w , in THz, needed to support the capacity reported in Table 1(a) for a target ACC $X = 50$. In parenthesis the expansion and juxtaposition factors L and K (being L and K numerically equal, only one value is reported).

such that $\delta_{ch} = \lfloor \frac{\Delta_{ch}}{BW} \rfloor = \frac{\Delta_{ch}}{BW_D}$. Similarly, let $fsr = \lfloor \frac{FSR}{BW_D} \rfloor$ be the discretized MRR *FSR*, let $fsr^{(\max)} = \lfloor \frac{FSR^{(\max)}}{BW_D} \rfloor$ be the discretized $FSR^{(\max)}$ and $efsr = \lfloor \frac{EFSR}{BW_D} \rfloor$ be the discretized *EFSR*. Since fsr and $efsr$ can be expressed as multiples of δ_{ch} , i.e., $fsr = h\delta_{ch} + n$ and $efsr = Mfsr$, the following equations must hold:

$$fsr = n \pmod{\delta_{ch}} \quad (1) \quad efsr = Mfsr = Mn \pmod{\delta_{ch}} \quad (2)$$

Eq. (1) and Eq. (2) derive from the definition of n and of $efsr$. Our objective is to find a triple $(h^{\max}, n^{\max}, M^{\max})$ maximizing $efsr$. Since M^{\max} represents the maximum number of times the fsr can be repeated before a channel matches again the MRR's TF, then $nM^{\max} = 0 \pmod{\delta_{ch}}$. It is easy to prove that the maximum $efsr$ is obtained if $M^{\max} = \delta_{ch}$, $h^{\max} = \lfloor \frac{FSR^{\max}}{BW_D} \rfloor$, $n^{\max} = \max_n \{fsr^{\max} \geq h^{\max}\delta_{ch} + n, \text{ s.t } \gcd(n, \delta_{ch}) = 1\}$, where $\gcd(x, y)$ is the greatest common divisor between x and y . Details are omitted due to space limitations.

5. Results

According to recent literature works, we considered MRRs with a minimum radius equal to $R_{\min} = \{5, 10, 100\} \mu\text{m}$, based on silicon waveguides ($n_g \approx 1.5$) and a BW equal to the minimum required for filtering the signal at the given bit rate. If TTxs perform basic NRZ modulation at bitrate R_b , the effective optical filtering bandwidth is $BW = 2R_b$. In addition, we considered channel spacings in $\Delta_{ch} = \{50, 100, 200\}$ GHz, compliant with ITU-T G.694.1 specifications. Table 1(a) shows the maximum aggregate capacity in Gbps for several R_b and Δ_{ch} . Smaller MMR radii ensure larger capacities due to the larger FSR^{\max} . The gain achieved by the *EFSR* extension technique is indicated in parenthesis and it is evaluated as the ratio between the capacity of a WRM exploiting the *EFSR* technique and a simple MMR-based WRM. The capacity gain is higher for higher channel spacings because it allows a larger δ_{ch} . A sensible gain in capacity is achieved with respect to the version without the *EFSR* technique, i.e., it is possible to achieve several Tbps if the technology employed allows the construction of MMRs with $5\mu\text{m}$ radius. Furthermore, the use of smaller bitrates leads to a slightly larger scalability, due to the larger granularity in the use of the spectrum. Table 1(b) shows the final TTx tuning range w in THz needed to support the aggregated capacities reported in Table 1(a), when a maximum ACC $X = 50$ is allowed [4]. Dashes are placed where the resulting w was higher than 60 THz, a value today unreachable by TTxs. In parenthesis, we reported the expansion and the juxtaposition factors K and L , which have the same value. Both strategies mitigate the ACC, but they have different impact on the TTx side. For instance, for $R_b = 40\text{Gbps}$ and MMRs with $5\mu\text{m}$ of radius, the ACC constraints ($X = 50$) can be satisfied either by the expansion strategy, employing TTxs with an extended tuning range of $W = 2 \times 6.3\text{ THz}$, or by the juxtaposition strategy, using 2 different sets of TTxs with $w = 6.3\text{ THz}$ each. In Summary, we proposed a MRR-based WRM for packet switching applications that is logically equivalent to a $N \times N$ AWG. We analyzed its physical limitations related to ACC, and feasibility limitations due to the technological constraints on the minimum MRR radius. We presented two strategies to limit the ACC, and we introduced the concept of equivalent FSR, which overcomes the technological limitations related to the MRRs geometry. The proposed WRM is promising in terms of scalability, and is a good candidate for future optical fabrics.

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