Space Division Multiplexing(SDM) in optical network

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1. *Questions & Answers:*

1.1. What is an SDM?

SDM refers to the multiplexing of orthogonal signals in the space domain and is a generic term for core-division and/or mode-division multiplexing.

1.2. Why do we need SDM technology in optical networks?

Over the last few decades, network traffic has consistently grown at an exponential rate and was efficiently satisfied using WDM and more efficient coding schemes requiring coherent detection. There is no indication that the network traffic growth trend will cease anytime soon, and we are nearing the day when the capacity of the ubiquitous single-mode fiber will be fully exploited. Space-domain multiplexing (SDM) for high-capacity transmission is the promising solution with the scaling potential to meet future capacity demands.

1.3. What are the possible techniques of SDM?

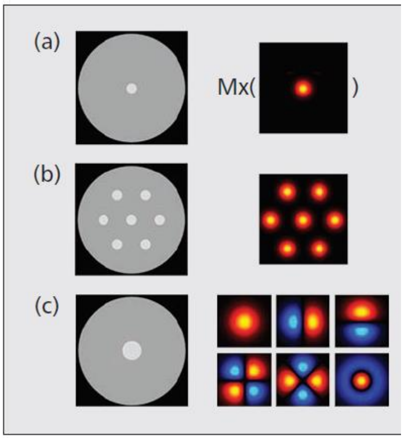
-Multi-core fiber(MCF): several cores within the same cladding (same fiber) are used to transmit independent data streams.

-Multi-mode fiber (MMF): different modes are used to transmit independent data streams.

-Few-mode fibers (FMF): like MMF but with 10 or fewer modes.

-Bundles of SMFs (BuSMFs).

-FM-MCF: merge the core and mode division technologies



1.4. How do the SDM fibers work?

As we know, MCF means there are multi cores inside the fiber, for each core, it has a corresponding waveguide contracted by the different refractive index between core and cladding, so we can realize SDM.

MMF means multimode inside one fiber, it can be realized by adjusting fiber parameters, for example, we can change the optical constraint of the core by changing the diameter of the fiber, so we can control the number of existing modes. We have the following formula:

$$□ = \frac{2□□}{□}\sqrt{□_{□□}^{2} - □_{□□}^{2}} ,$$

where ρ is the radius of the core of the fiber. If V<2.405 => single mode fiber
M ~ □^{2}/2 (estimation of number of modes)

1.5. *What does the different type of noise affect the transmitted signals ?*
-Cross talk. (There is trade-off between reducing the XT and minimizing the cladding size)
-XPM (Cross Phase Modulation)
-Coupling effects.
-Group delay

1.6. *What are the advantages/disadvantages of SDM compared with other multiplexing methods?*
-Benefit from the space dimension to increase the used link capacity.
-The use of space-time codes and FEC to enhance BER.

Multi-core	Multi-mode solid core	Multi-mode hollow core
+ Highest data rates achieved so far	+ Potentially lowest system cost	+ Lowest latency (<-30%)
+ Enabling higher density of integration for transponders and amplifiers	+ Enabling higher density of integration for transponders and amplifiers, ROADMs	+ Enabling higher density of integration for transponders and amplifiers
+ Can be combined with multi-mode	+ Higher reach due to lower nonlinearity	+ Lowest potential loss (<0.1dB/km) @ 2 µm
- No advantage in reach (same loss, nonlinearity)	+ More efficient pumping than multi-core	+ 4 x bandwidth @ 2 µm
- Same bandwidth as SSMF	- Same bandwidth as SSMF	+ Very low nonlinearity
- Fiber crosstalk needs to be further reduced	- Equalization of mode cross talk required in DSP	- Mode dependent loss is intrinsic and leads to performance degradation
- No ROADM integration	- Mode dependent loss can lead to performance degradation	- Very high differential group delay requires huge DSP complexity for mode multiplexing
	- Scalability to higher number of modes is tough	- No long reaches demonstrated so far (record reach <1 km)
		- Losses so far are well above SSMF

-Hard to produce and expensive.

1.7. *What limits the use of SDM in optical fiber?*
1. *for MMF (using FMF: few mode fiber)*
   Interference between modes, differential group delay, and mode-related loss make it difficult to receive and demodulate mode multiplexed signals
2. *for MCF (using MCF: Multi Core Fiber)*
   Difficulty in production, limited precision
   Also, mechanical constraints can limit the number of cores used as there is a limit on the fiber diameter.

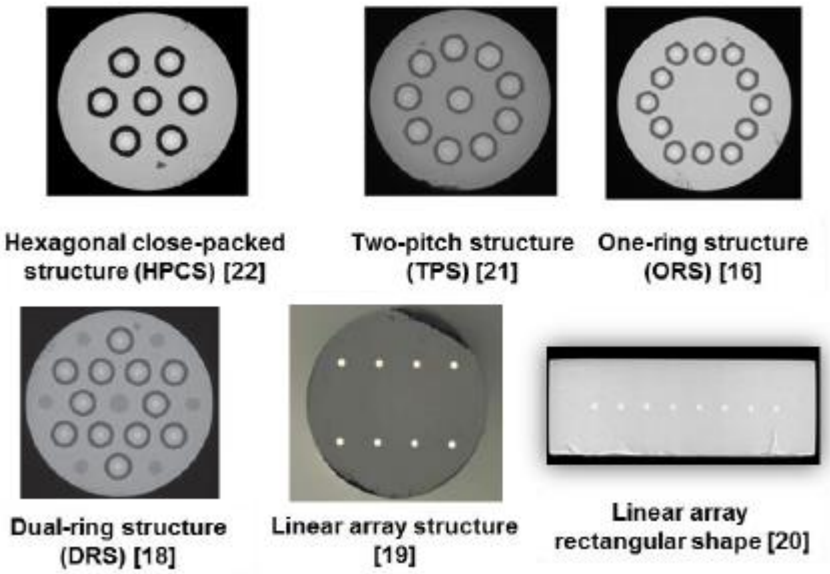
1.8. *What modulation methods can be used for SDM?*
Several kinds of modulation can be used as SDM does not introduce limitations on modulation techniques. (examples found in the articles: PD-QAM16, QAM-4,...).

1.9. *How can we reduce DSP complexity for SDM?*
The Digital Signal Processing is used at the receiver side to separate the different receiving modes. (the complexity of the DSP increases by increasing the coupling between the modes).

Complexity can be reduced by weak coupled modes in FMF.

1.10. What optical devices and components are used for the SDM communication system?

-SDM fiber. e.g., MMF, MCF.

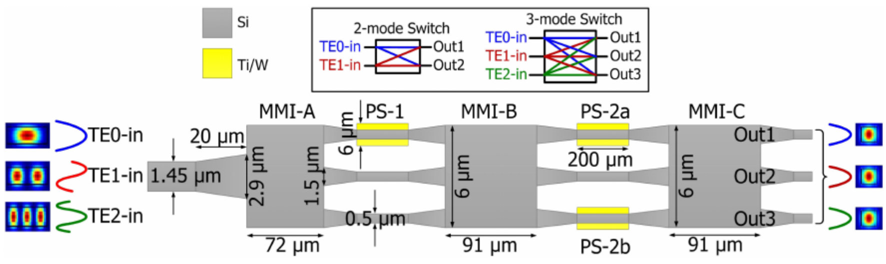


Different MCF Arrangements

-SDM Amplifiers: Amplification is a crucial task in optical long haul communication. There exist several solutions for SDM amplification. Examples on these solutions are:

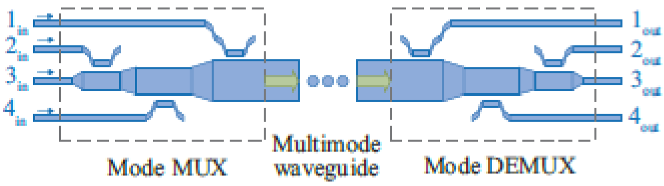
- Pumped-distributed Raman amplifiers for few modes and long-haul MCF.
- EDFA are developed for fiber bundles, FMF, and MCF.

-We have a type of photonic switch which can be used as mode convertor, In the paper, scientists have realized a reconfigurable switching between the first three TE (TE0, TE1, TE2)modes using the same device.



SMS: Scalable multimode switch

-Spatial multiplexers/demultiplexers (MUX/DeMUX), where SMFs are coupled with MCF and MMF.

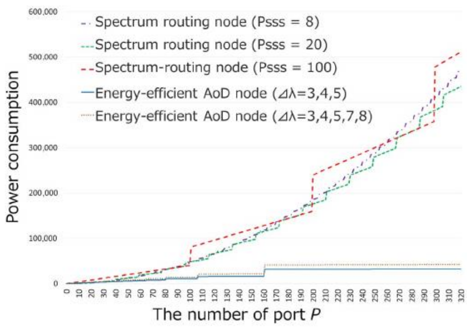


Multi-mode Mux and DeMux Based on Asymmetric Directional Coupling

-SDM transmitters and receivers.

1.11. *How can the SDM improve the energy efficiency? Or what technologies does the SDM adopt to improve the energy efficiency?*
(paper 6)
traditional : SSS (spectrum selective switch)

Energy-efficient AoD(Architecture on demand)
the flexibility of AoD nodes can also be used to reduce the power consumption of optical nodes. Because AoD nodes are dynamically constructed according to the switching request, they can use just enough modules, although traditional architectures constantly require a fixed maximum number of hard-wired modules regardless of the request. It is possible that the use of AoD nodes can reduce the number of implemented modules and the power consumption.



1.12. *For MMF, how can we separate different modes in the receiver?*
Spatial demultiplexers (DeMUX) can be used.

1.13. *What is Spatial Superchannel (SSC)?*
SSC refers to the grouping of M signals that provides M time more bandwidth in a single operation cycle with means of SDM.

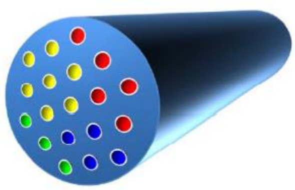


Fig. 7. Example of four sliced spatial superchannels.

1.14. What are the advantages of Spatial Superchannel (SSC)?

a) It can share hardware and DSP resources for each subset.
b) It can be extended to new spatial modulation formats that enable greater design flexibility by increasing the number of dimensions over which the optical modulation is applied. because we can constitute a subset of cores referred to as SSC, the number of cores inside each subset can be chosen, as shown in the figure.

1.15. Are there some SDM transmission experiments realized? What's the capacity?

SDM transmission was realized using:

a) Homogeneous SMF-MCF.
b) Heterogeneous FM-MCF.

In 2015, the capacity record was doubled to 2Pb/s in two experiments.

a) They used a 31.4km a 22-core fiber in communication a wideband optical frequency comb source
b) The other used a 9.8km 19-core six mode fiber where each mode carried 360 C-band wavelength channels spaced at 12.5GHz with each channel carrying

1.16. What's the application of SDM?

SDM fibers open up new possibilities for advanced SDM applications that more efficiently share both physical and DSP resources between channels and thus improve the flexibility and efficiency of short- to medium-haul optical fiber transmission.

For example

a) spatial superchannel
b) Another advanced application of SDM that promises savings in hardware and DSP resources is self-homodyne detection (SHD)

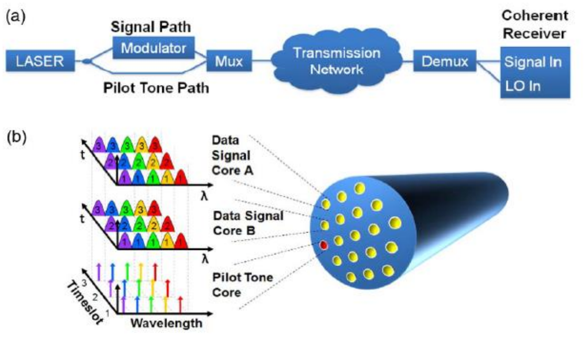


Fig. 8. (a) Schematics of a self-homodyne transmission system. (b) Signal distribution in data-signal cores and the pilot-tone core.

c) Finally, a third network enhancement instituted by SDM could be wavelength contention management solely done in the optical domain.

1.17. What are the challenges for the SDM technology?

a) How to mitigate the crosstalk is the major problem
b) The development of suitable equipments
c) Production of equipment with a low financial cost

1.18. How can we evaluate the crosstalk of a multi-core fiber?

We can use the following formula to calculate it:

$$XT = \frac{n - n.exp[-(n+1).2hL]}{1 + n.exp[-(n+1).2hL]}$$

$$h = \frac{2k^2 r}{\beta w_{tr}}$$

h is the increment of crosstalk per unit length, k is the fiber coupling coefficient, r is the curvature radius of the fiber, beta is the propagation constant and wtr is the distance between cores (core pitch). n is the number of adjacent cores (neighboring cores) and L is the fiber length.

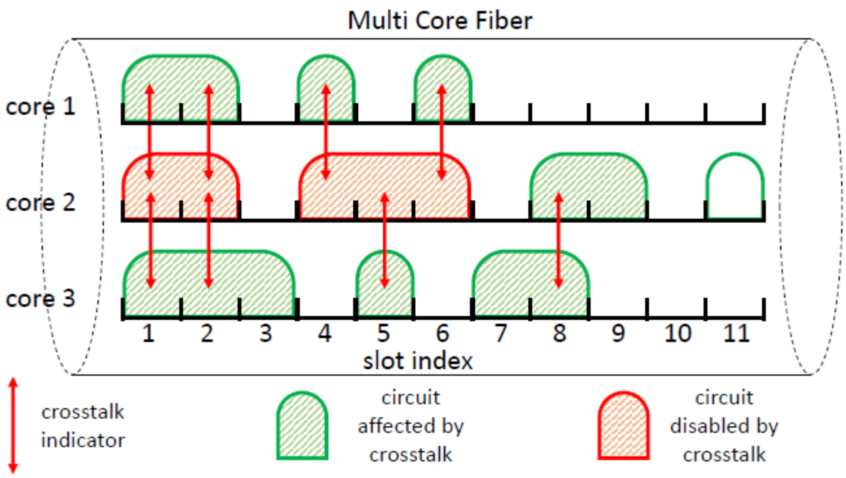
1.19. *How can we reduce the effect of crosstalk for a multi-core fiber?*

a) *Reasonably design the structure of multi-core fiber, for example, such as Trench-Assisted MCF*

b) *Reasonably arrange the circuit slot for neighbouring cores*

The circuits allocation does not occur in slots whose index is the same

of slots allocated in neighboring cores, avoiding interference.



In the figure, it is observed that the core 2 suffers greater crosstalk interference, since the two adjacent cores (1 and 3) present some circuits allocated in similar intervals of slots, as for example the slots 1, 2, 4, 5 and 6.

2. ***The objectives:***
   2.1. *Clear definition of SDM and its characteristics.*
   2.2. *The structure of the SDM communication system.*
   2.3. *The Used SDM techniques.*
   2.4. *The noise exists in the SDM. And how to eliminate them.*
   2.5. *Advantages and drawbacks.*
   2.6. *Practical example of SDM.*

3. ***The strategies to solve the questions.***
   3.1. *Read the provided papers.*
   3.2. *Turn to the Internet for help.*
   3.3. *Schedule meetings to discuss and answer the questions.*

4. ***Presentation:***
   4.1. *Start talking about what colleague already knew (WDM and TDM for example)*
   4.2. *SDM def*
   4.3. *MMF and MCF (their characteristics, advantages, dis-)*
   4.4. *Experimental*
   4.5. *Implementation(devices can be used)*
   4.6. *Challenges*
   4.7. *Application (advanced)*